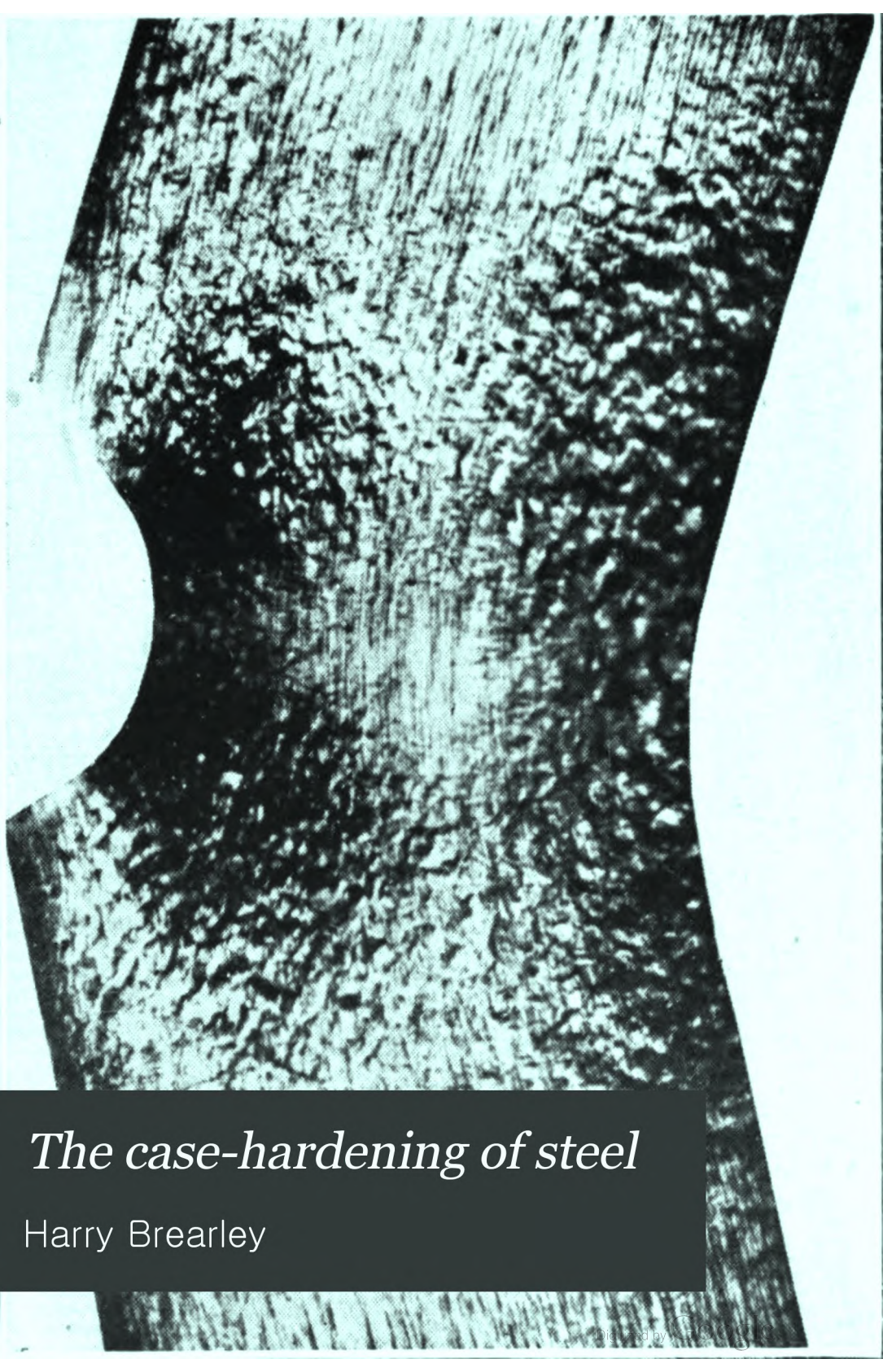
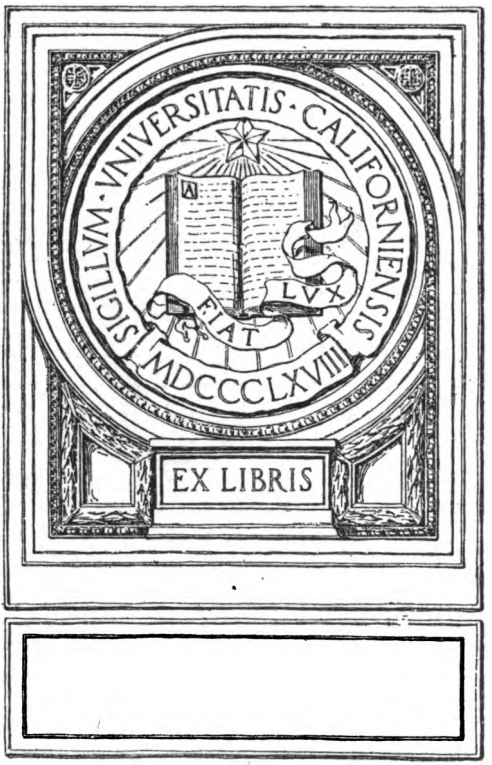


The case-hardening of steel

Harry Brearley



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THE CASE-HARDENING OF STEEL.

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THE CASE-HARDENING OF STEEL

AN ILLUSTRATED EXPOSITION OF THE CHANGES IN STRUCTURE AND PROPERTIES INDUCED IN MILD STEELS BY CEMENTATION AND ALLIED PROCESSES.

BY

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To My Old Friends

N.B. and J.T.

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PREFACE.

THE following descriptions and explanations were written mainly for the use of those actively engaged or interested in the commercial production of case-hardened objects. For that reason the chapters are arranged so as to appeal at once to the workshop experience and observations of craftsmen, to whose friendliness the author is indebted for many of the specimens from which the illustrations were made. It was not found possible, however, to separate the subject into practical and theoretical divisions, nor is any such distinction desirable.

Though no apology may be needed for introducing a number of micro-photographs, a few words of explanation may be allowable by way of familiarising the use of polished and etched surfaces, whether they are to be observed by the naked eye, through a hand lens, or by more elaborate magnifying outfits.

When an object breaks, or is proved unsuitable for its purpose on account of faulty design, there is no difficulty in realising the fact, because the design can be clearly seen. The want of sufficient hardness can also be realised, because simple means are available for measuring and comparing the hardness of various substances. And an object which fails because it was made from unsuitable material, or otherwise from suitable material badly handled, is an enigma only so long as we have no means of measuring or comparing the properties on which its suitability depends. We know, for example, why boiler plates and razors should not be made from the same kind of steel, and can predict beforehand in what respects they would prove unsatisfactory if they were.

We are accustomed to discriminate between certain kinds of materials by the appearance of fractured surfaces; the tool steel trade was built up on refined discriminations of this kind long before chemical analysis or the modern refinements of heat treatment had been developed to any serviceable extent. The observation of polished and etched surfaces is nothing more than an extension of this old and useful practice, and quite a remarkable amount of information can be extracted from such surfaces by means of a hand lens magnifying only five or six diameters, and sometimes even by the unaided eye.

It is unfortunate, though perhaps not altogether unavoidable, that microscopic demonstrations should be obscured by a

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jargon of ambiguous names. But the examinations themselves are not in the least ambiguous; on the contrary, they are along the line of least resistance for whoever wishes to study the principles underlying metallurgical handicrafts, and provide unrestricted opportunity for direct observation, which may be interpreted according to one's personal experience. The necessity for such observations lies mainly in the planning of schemes for attaining some desired end and in the quest of the intelligent mind after the why and wherefore.

An explanation based on the mechanical structure of an object is intelligible, because most minds can appreciate the elements of design and pass judgment on the composite properties of materials. All kinds of steel have a mechanical structure which, when suitably magnified, is as obvious as that of reinforced concrete. It is in terms of such structures that the properties of case-hardened steels must be explained. For that reason micro-photographs will be freely used in the following pages; and for the same reason the assistance offered by microscopic methods, whatever means of magnification are available, should not be ignored in workshop practice.

H B

OLD WHITTINGTON,
NEAR CHESTERFIELD.

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CONTENTS.

PAGE

PREFACE .. .. vii.

PART I.

HISTORY AND MEANING OF CEMENTATION.

CASE-HARDENED FILES — CEMENTATION AND CAST STEEL — SHEAR STEEL — STRUCTURE OF STEEL — PEARLITE — CEMENTITE .. 1

PART II.

STRUCTURAL CHANGES IN THE CORE.

OVERHEATING — REFINING — CHANGES ON HEATING — COMPLETE DIFFUSION — CHANGES ON COOLING — DOUBLE QUENCHING .. 7

PART III.

FIBRE AND LAMINATION IN THE CORE.

WHAT IS FIBRE? — FIBROUS CORES — FINAL QUENCHING — FIBRE STEELS — TRANSVERSE CRACKS — LAMINATION — SLAG STREAKS 24

PART IV.

PROPERTIES AND DEFECTS OF HARDENED CASES.

FREE CEMENTITE — REFINING THE CASE — SUPER-CARBURISATION — SLAG STREAKS — HARMFUL FIBRE — SOFT SPOTS — TROOSTITE — GRINDING — STREAKY TROOSTITE — CRACKS AND SPLINTERS 34

PART V.

THE CARBURISING OPERATION.

FURNACES — BOXES — CONDUCTIVITY OF MIXTURES — SOFT PLACES — CARBURISATION — ACTION OF GASES — DECARBURISATION BY GASES — SLOW COOLING — DEPTH OF PENETRATION — PENETRATION CURVES — PHOTO RECORDS OF PENETRATION .. 51

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PAGE

PART VI.

CASE-HARDENING STEELS.

MACHINED SURFACES — CAUSE OF ROUGH FINISH — CARBON STEELS — MANGANESE STEELS — CHROMIUM STEELS — NICKEL STEELS — NICKEL-CHROME STEELS 66

PART VII.

CARBURISING REAGENTS.

EQUILIBRIUM DIAGRAM — HELPFUL SCEPTICISM — SOLID CARBURISERS — DIAMONDS — EVOLVED GASES — USELESS GASES — DISCREPANCIES — A GOOD CARBURISER — ALKALINE CHARCOAL — CHARRED BONE — GASEOUS CARBURISERS — SPRINKLING POWDERS 77

PART VIII.

METHODS OF TESTING.

HARDNESS: FILE TEST — SCLEROSCOPE — BALL TEST — BRINELL MACHINE — HARDNESS OF BAR STEEL — TOUGHNESS OF BAR STEEL — IZOD IMPACT TESTER — CONSTANTS OF IZOD MACHINE — NOTCHES AND CRACKS — HIGH IMPACT FIGURES — ROUND AND SHARP NOTCHES — CREEPING CRACKS — MAXIMUM TOUGHNESS — STRENGTH OF HARDENED CASE — RING CRACKS — NO TOUGHNESS WITHOUT DISTORTION 95

PART IX.

AUTOMOBILE STEELS.

CHEMICAL COMPOSITION — PHYSICAL PROPERTIES — CHANGES BY HEAT TREATMENT — HIGH QUENCHING HEATS — SERIES HEAT TREATMENTS — TEMPERING ALLOY STEEL — BUYING MECHANICAL PROPERTIES — SELECTION OF MATERIALS — CARBON STEELS — NICKEL STEELS — NICKEL-CHROME STEELS — SKILFUL HANDLING — VANADIUM STEELS — AIR-HARDENING — IRREGULARITIES OF AIR-HARDENING 116

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PART X.

HARDENING AND TEMPERING.

UNIFORM HEATING AND COOLING — ANGLES AND CORNERS — FORMATION OF CRYSTALS — SHRINKAGE — SHRINKAGE CRACKS — COMPRESSION CRACKS — STEEL BALLS — DISTORTION — TENSILE TESTS — LOSS OF HARDNESS — WORKING FURNACES — PYROMETERS — PROTECTION FOR COUPLES — TEMPERATURE INDICATORS — TEMPERATURE RECORDERS — SENTINELS — QUENCHING FLUIDS 137

PART XI.

SURFACE HARDENING WITHOUT CEMENTATION.

PRESS HARDENING — FLAME CUTTING — BLOWPIPE HARDENING — TAPER HEATING 161

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ILLUSTRATIONS.

FIG.		PAGE
1.	Section through cemented part of case-hardened bar ..	4
2.	Structure of dark parts of fig. 1. ×1,200	5
3.	Overheated structure of mild steel. ×25	8
4.	Plan of method used to study refining process	9
5.	Peg quenched at 750° C. on heating	10
6.	Portion of fig. 3 highly magnified	10
7.	Portion of fig. 5 highly magnified	11
8.	Peg quenched at 780° C. on heating	12
9.	Peg quenched at 800° C. on heating	12
10.	Peg quenched at 850° C. on heating	13
11.	Figs. 5 and 10 both photographed at 100 diameters, then reduced	14
12.	Peg quenched at 800° C. on cooling	15
13.	Peg quenched at 760° C. on cooling	16
14.	Peg quenched at 740° C. on cooling	16
15.	Peg quenched at 670° C. on cooling	17
16.	Any peg withdrawn below 670° C. on cooling	18
17.	Overheated steel before and after refining	18
18A.	Mild steel quenched from 800° C. after previous quenching from 920° C.	20
18B.	Mild steel quenched from 800° C. after cooling slowly and reheating	20
18C.	Mild steel quenched from 800° C. after cooling to that temperature from 920° C.	21
19.	Fine crystalline core in case-hardened bar	25
20.	Fractures of bars quenched in water (right) and oil (left) ..	27
21.	Diagrammatic representation of impact tests	28
22.	Showing how seams, etc., affect resistance to fracture ..	28
23.	Wrought-iron containing slag streaks. ×150	30
24.	Laminated fracture in case-hardened wrought-iron	31
25.	Slag globule in ferrite envelope	32
26.	Slag streaks in ferrite bands	32
27.	Coarse crystalline appearance of fracture due to free cementite	35
28.	Micro-photograph of extreme edge of fig. 27	35
29.	Crack proceeding along cementite outlines	36
30.	Cementite in needles and cell walls in quenched specimen ..	37
31A.	Bar cemented at 1050° C. for eight hours	39
31B.	Same bar as 31A reheated twelve hours at 1,000° C. ..	39
32.	Fibrous fracture along length of case-hardened die	41
33.	Dark-etching outline indicating soft part	43
33A.	Troostite in hardened file (Stead)	43
34.	Troostite fringe on the edge of soft spots	44

Digitized by Google

Fig.		Page
35.	Troostite fringes within the core	45
36.	Grinding sparks caught on glass plate	47
37.	Streaky troostite due to grinding	48
38.	Fringe on edge of joiner's chisel	49
39.	Soft splinter on hardened ring	49
40.	Cracks in flat surface of ground washer	50
41.	Heat conductivity curves of wood charcoal and Caron's mixture	53
42.	Middle part of bar shielded from carburising effect	56
43.	Section of bar in contact on one face only with case-hardening powder	57
44.	Quenched bar with sharply defined carbonless envelope ..	59
45.	Thickening of carbide plates in pearlite areas due to slow cooling	60
46.	Cementite envelope in slowly cooled mild steel	61
47.	Degree and depth of carburisation as determined by chemical analysis	62
48.	Degree and depth of carburisation as seen on polished and etched section	63
49.	Entire cross section of case-hardened bar	64
50.	Steel which machines well	68
51.	Similar steel to fig. 50, which machines badly	69
52.	Guillet's diagram of nickel steels	73
53.	Varying structures in cemented bar of six per cent. nickel steel	74
54.	Equilibrium diagram	78
55.	Mr. Stead's pictorial diagram	79
56.	"Blackheart" malleable iron	86
57.	Arrangement for testing carburisers	87
58.	Heating curve of greasy bone black	88
59.	Time-penetration curves	89
60.	Phosphide blisters on cemented gear	91
61.	Microstructure of phosphide blister	92
62.	Brinell hardness-testing machine	100
63.	Ball holder for simplified form of Brinell test	101
64.	Izod impact testing machine	103
65.	Irregular impact figures are obtained from coarsely crystalline material according as the bottom of the notch falls on or on either side of a crystal junction	105
66.	Distortion in impact test piece	107
67.	Fracture into piston head	109
68.	Creeping crack in waggon axle	110
69.	Forces needed to break bars having crystalline and "fibrous" cores	112
70.	Ring cracks on bent case-hardened bar	113
71.	Section of cemented impact bar	114
72.	Different fractures from the same steel	117
73.	Mechanical properties of mild steel after different forms of heat treatment	122
74.	Mechanical properties of nickel-chrome steel after different forms of heat treatment	123

Digitized by Google

Fig.		Page
75.	Comparative behaviour on tempering of carbon steel and nickel-chrome steel	124
76.	Effects of initial cooling temperature on chromium steel ..	132
77.	Effects of initial cooling temperatures on nickel-chrome steel	134
78.	Effect of rate of cooling on thermal and magnetic changes ..	135
79.	Polished and etched section of chrome steel ingot	139
80.	Crystal outlines about corner in quenched bar	140
81.	Clay model of crucible steel-making furnace	141
82.	Crack between hard and soft parts of flat bar	142
83.	Effect of hardening stresses on sharp corners	143
84.	Splintered teeth of milling cutter caused by hardening ..	144
85.	Sharp corners in steel disc	145
86.	Cracks and fracture due to compression	146
87.	Effect of surface tension of water on immersed ball	147
88.	Disc of mild steel distorted by repeated quenching	148
89.	Heating and cooling curve made on works recorder	155
90.	Sentinel and saucer	157
91.	Hard surface of steel cut by blowpipe flame	162

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I.

HISTORY AND MEANING OF CEMENTATION.

SINCE the advent of the bicycle and the motor car, the practice of case-hardening mild steel has become of great commercial importance, though it is by no means a modern art. A number of workshop tools, such as reamers, drifts, and gauges, can be, and are now, made very satisfactorily from case-hardened mild steel; but long before the steel age the same principles were made use of in the manufacture of the humble file. A piece of iron of suitable shape was provided with irregular teeth, and after being wrapped in dried skin or wound in a leather strip was heated at first slowly and finally to full redness, and then quenched. So that something like charred leather was used as a case-hardening medium in this way long before users had any cause to complain of the marketable material containing hob nails, sprigs, and brass eyelets.

CASE-HARDENED FILES.

Nothing appears to be known definitely about the earliest uses of case-hardening, although it is said to have been in use amongst the Chinese during the eighth century. In the latter half of the ninth century, however, the art was so far advanced that a Benedictine monk—Theophilus Presbyter—wrote a book in which precise instructions were given for the case-hardening of files. The mixture he recommended was made from three parts of charred horn meal and one part of salt. This material was to be strewn over the heated file, and then, after again reheating, the file was quenched in water. This process may still be seen in everyday use in certain parts of Russia, where files are made from mild Bessemer steel. The mixture of horn meal and brine with perhaps a small quantity of lampblack or other unimportant ingredient is made into a thick paste, and brushed over the cut files. After the paste has completely dried, the files are heated over a breeze fire; when the salt melts and the paste becomes semi-fluid it is brushed off, and the files are quenched out.

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Such files are always case-hardened on the tips of the teeth at least: they would not cut effectively otherwise. Being made from mild steel, teeth are easily formed on them, even if the file blanks have not been well annealed, and the cutting chisels last a longer time. As the steel is softer than that generally used in England for file-making, the tooth thrown up by the impact of the cutting tool flows to a sharper edge, and so long as the extra sharp edge persists, such a file will cut quicker than the blunter-toothed file made from harder steel. Only the edge of the tooth is cemented during the hardening operation, and only the fine edge is worn off on file-testing machines; hence the apparent superiority of the mild steel file, according to machine-made tests. In actual practice, however, a file is worn much further, and the life of the mild steel file is comparatively short.

The name of Reaumur is usually associated with the production of malleable iron castings, but he appears to have been led to that subject whilst he was investigating the conditions most favourable to the production of steel by the old cementation process. He found that the most effective case-hardening or cementing material could be produced by mixing together charcoal powder, wood ashes, and sea salt. He observed that the case-hardened article increased in weight, and ascribed that increase to combination of salt and sulphur with the iron. He noticed also that after repeated or prolonged heating, the cemented steel would not harden, and this he ascribed to the loss by volatilisation of the salt and sulphur which had been previously taken up by the iron. Pig iron, according to this idea, was a material containing a very large amount of salt and sulphur, which, he thought, might also be driven off by prolonged heating; in this way he arrived at the production of malleable iron castings, which, according to his theory, lost a large part of the sulphur and salt they contained by prolonged heating (in an oxidising atmosphere).

CEMENTATION AND CAST STEEL.

Reaumur appears to have overlooked entirely the possibility of the carbon combining in any way with the iron, though he knew that it (charcoal) was a necessary constituent of his case-hardening mixture. But although his explanations were wrong, his reasoning was sound. He argued that if steel might be prepared by combining sulphur and salt with soft iron, or by driving sulphur and salt from

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its combination with pig iron, it should be possible to produce steel by a third process, viz., the melting together of the two substances which contained respectively much and little of the essential sulphur and salt; and this he actually did by first melting the pig iron and adding then nails and other small wrought iron objects to it.

In this sense Reaumur may be regarded as the originator of cast steel, though his process was superseded by that of Huntsman, who twenty years later—in 1740—introduced the practice of melting cemented bar iron. To Reaumur's credit, however, it should be said that the melting of wrought iron with some carburising material is now by far the most commonly used method of producing crucible cast steel. The Huntsman process of making cast steel consists, strictly speaking, of first cementing the wrought iron and then melting it in a crucible. The Reaumur process consists of melting together wrought iron with a carburising material such as pig iron. What should be especially noted in this preamble is that the process of cementation or case-hardening is not only of great antiquity, but has always been of great importance, and was the direct incentive and predecessor of the comparatively modern art of making cast steel.

Although the process of cementation or case-hardening is essentially the same to-day as it was a thousand years ago, our explanations differ greatly from those offered by Reaumur two centuries ago. We know that the operation consists of combining carbon with iron by heating the two substances together, and we find by careful experiment that the iron increases in weight by an amount about equal to the weight of carbon which has combined with it. How the carbon combines with the iron, not only on the surface, but at depths of ten or even twenty millimetres below the surface, is a question which had better be left until observation has made us familiar with more facts.

SHEAR STEEL

At any rate, we know that the aggregation of like crystals composing pure iron is invaded by dark areas containing carbon (as iron carbide), whether the iron is melted with the addition of charcoal in a crucible and cast into ingot form or whether the iron and charcoal are heated together short of melting. Any distinction between the two kinds of steel depends on incidentals. When the Sheffield cutler takes up a table knife to read the inscription on the blade, as he has a habit of doing, and remarks that the blade has

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been made from shear steel, he depends on the unavoidable presence of long drawn-out slag streaks in steel made from cemented bar iron which has not been subsequently melted; without the tell-tale slag streak neither a cursory glance nor a fairly extended examination by other means enables one to determine exactly by what process the steel has been made.

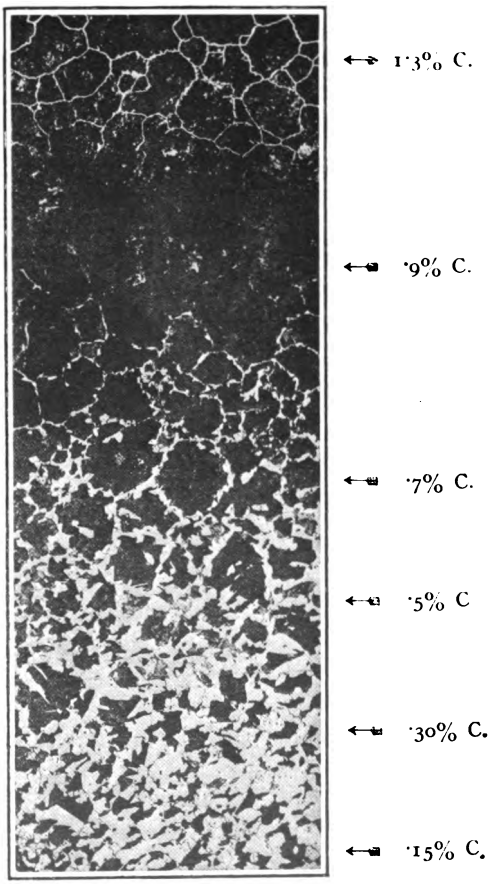

FIG. 1.—Section through cemented part of case-hardened bar.

STRUCTURE OF STEEL.

In the composite photograph of a case-hardened section (fig. 1) we have a picture of the characteristic structure of all kinds of carbon steel, from the softest to the hardest, to be found in commercial use. It will be helpful later if

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we pause now to observe that the material is made up of irregularly shaped crystalline grains which cohere strongly to each other, and that at the foot of the picture there are a few dark patches containing practically all the carbon which existed in the original bar. The case-hardening has not changed in the least the composition of the material at that depth below the surface. The carbon has, however, penetrated into the upper layers, and it is to be observed that the dark patches occupy a relatively greater area as the amount of carbon in the succeeding layers, progressing outwards, increases. This continues in strict ratio until the

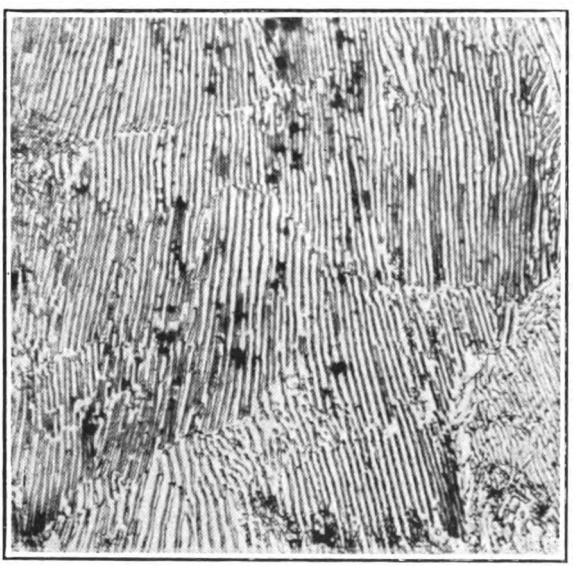

FIG. 2.—Structure of dark parts of fig. 1. x 1,200.

carbon content reaches about .9 per cent., at which point the entire layer is a continuous dark patch, with no other visible constituent to mark the crystalline outlines or form any discernible pattern whatever.

PEARLITE

But the dark patches are not as elementary and structureless as they appear to be. When the steel is allowed to cool slowly in the case-hardening box the dark patches have a simple but well-defined structure of their own. It is distinctly visible at high magnifications only, and under normal

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circumstances, after suitable etching, has the appearance of black and white lines arranged alternately and roughly parallel to each other within any single crystalline grain, though from grain to grain the direction of the parallel lines may change (fig. 2). Each alternate member of this compact arrangement consists of carbide of iron; the other constituent is supposed to be pure iron. These alternated substances are so minute and well defined that they break up light waves and assume a pearly appearance, for which reason they are known as "pearlite."

From the core of the case-hardened bar (fig. 1) outwards the material consists of an irregular conglomeration of white patches, which are pure iron, and dark patches, which are pearlite, until nearer the extreme surface the material is composed entirely of pearlite. But the picture contains another constituent which ought not to occur to an appreciable extent in case-hardened objects. When it does occur it leads generally to trouble, and it will be necessary later to determine how its unwelcome presence may be avoided. But at present we need only observe that its occurrence, whether welcome or otherwise, is a natural sequence to the observations already made.

CEMENTITE. If all the free iron, which is the basis of our steel making, has been already used up in the formation of the sandwich-like pearlite by the time the amount of carbon it contains reaches only .9 per cent., then clearly, if any further amount of carbon can possibly be introduced into steel it must adapt itself to some new and separate form of existence. And it does so to the extent that, as no iron is available with which to form pearlite, the surplus carbide exists alone and isolated in the form of either envelopes around the crystalline grains or as needles or small nodules within the crystalline grains.

It need only be said that ferrite or pure iron is soft and tough, that carbide of iron is extremely hard and brittle, and a mental picture can be readily formed of the mechanical properties of:

Mild steels, which contain much free ferrite.

Steels consisting entirely of pearlite, in which the brittle carbide is always sandwiched between two pliable neighbours.

Steels containing free carbide of iron (or cementite) as a hard brittle envelope separating one composite pearlite grain from another.

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II.

STRUCTURAL CHANGES IN THE CORE.

THOUGH the practice of cementation has almost ceased to exist as a steel-making operation, it flourishes exceedingly as a case-hardening operation applied to mild steels. The practice finds favour because quantities of small objects can be readily machined from soft steels, because it may be easier, *i.e.*, safer, to harden a cased object than one made from high carbon steel, or because a case-hardened object is for many purposes more reliable on account of the soft steel core. The condition of the core or uncarburised portion is of first-rate importance, and the aim in most cases is to bring it into a comparatively soft and fibrous condition, whether it is associated with an armour plate weighing many tons or a small rivet weighing only a fraction of an ounce.

OVER-HEATING.

As cementing operations cannot be effectively carried out at a temperature much below 900° C., and occupy lengths of time varying, say, from one hour to ten days, the steel is overheated both in the core and the case. If quenched directly from the case-hardening box signs of overheating are visible in the coarse crystalline fracture such articles always possess. The casing is brittle and apt to shell off or crack, and the core is not very resistent to sudden shocks. Cementation, to more than a superficial degree, cannot be accomplished except at such temperatures as overheat the steel and produce coarse crystals in it. But the structure can be refined, and the following extreme instance has been chosen to illustrate the nature of the changes involved in the refining operation.

A piece of steel as cast, or a forged bar of mild steel when badly overheated, and slowly cooled consists of crystalline grains of irregular outline whose internal structure, as seen within the white boundaries of ferrite, is remarkably uniform. Fig. 3 might be taken to represent a section cut from an overheated bar or from a mild steel casting. Whether we wish to refine the crystalline structure of a casting or an overheated steel bar, the principles of the process involved are the same, and may be illustrated by the changes occurring

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in the structure of material represented by fig. 3. This piece of steel contained .29 per cent. carbon and .64 per cent. manganese.

REFINING. The centre piece of fig. 4 may be taken to represent a block of steel weighing anything from ten to twenty-five pounds. A large central hole, to accommodate a thermo-couple which is attached to a recording pyrometer, has been made, and a number of small holes have been bored into its side. Into these small holes a number of pegs made from the overheated steel are inserted, and the centre block with pegs and couple is located inside a gas-fired furnace, which,

FIG. 3.—Overheated structure of mild steel. x 25.

by means of a special piece of apparatus, can be heated or cooled with perfect regularity at the rate of 50° per hour, or at any slower or quicker rate as may be desired. If, then, at certain intervals of temperature one of the pegs is withdrawn and rapidly quenched in cold water, we shall fix in it something like the kind of outline structure which existed at the moment of withdrawal, and after polishing and etching the structure of the peg can be examined under the microscope or photographed for record purposes. The arrows and numbers on the curve shown in fig. 4 represent the times and temperatures at which pegs were withdrawn, and it may

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be noticeable also that the curve shows clearly the critical thermal ranges both on heating (C) and cooling (R) at which the pearlite in the large block was transformed into something else (on heating) and again resumed its original form (on cooling). These physical changes, corresponding to the jogs C and R in the curve, are known respectively as the calescence and recalescence changes.

CHANGES ON HEATING.

All the pegs withdrawn before the temperature reached 700° C. were unaltered either in structure or any other determinable property. The peg withdrawn at 720° C. did not vary in any essential respect from the original material represented by fig. 3. In the peg withdrawn at 750° C. the general structure still remained the same (fig. 5), but the peg was now found to be comparatively hard to file, and would break rather than bend if gripped in a vice and

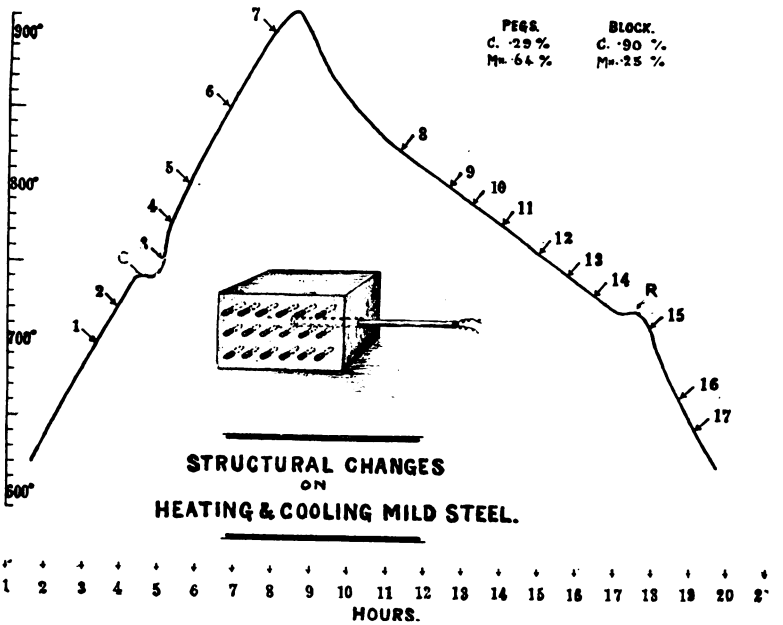

FIG. 4.—Plan of method used to study refining process.

struck with a hammer. Some change had obviously occurred, the nature of which may be discoverable. On examining suitably prepared sections under the microscope it was found that, whereas the original material observed at large magnification was striated in the pearlite areas, as seen in fig. 6,

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FIG. 5.—Peg quenched at 750° C. on heating. x 25.

FIG. 6.—Portion of fig. 3 highly magnified.

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the striation or lamellæ in the peg quenched out at 750° C. have diffused into each other, and are no longer visible, nor do they exist as such (fig. 7). The peg is quite as hard as hardened tool steel in the patches previously occupied by the pearlite, although the ferrite or pure iron areas are not appreciably harder than before.

From this point onward the transformed pearlite and the free ferrite adjacent to it diffuse into each other, and the undisturbed sharp outline between one constituent and the other, which is so obvious in fig. 5, after quenching at

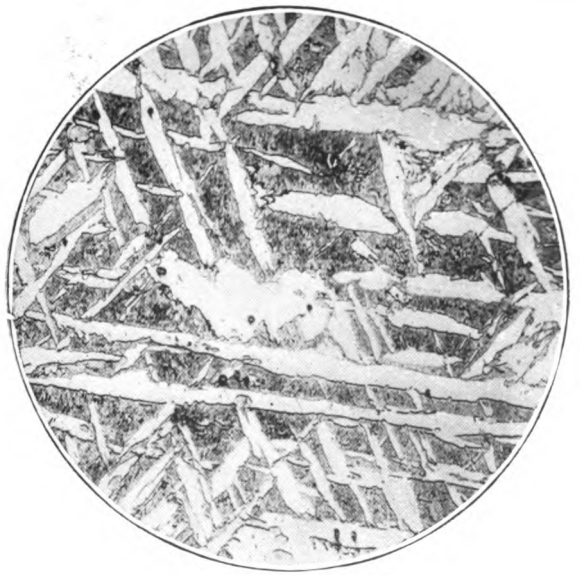

FIG. 7.—Portion of fig. 5 highly magnified.

750° C., is considerably disturbed in the piece quenched out at 780° C. (fig. 8). This inter-diffusion takes time to reach a state of equilibrium corresponding to any particular temperature, but once that equilibrium has been established a further lapse of time does not alter the structure. With further rise in temperature, however, the degree of inter-diffusion increases, and at 800° C. is so far advanced (fig. 9) that only a faint suggestion of the original coarse crystalline outline can be distinguished.

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FIG. 8.—Peg quenched at 780° C. on heating. x 25.

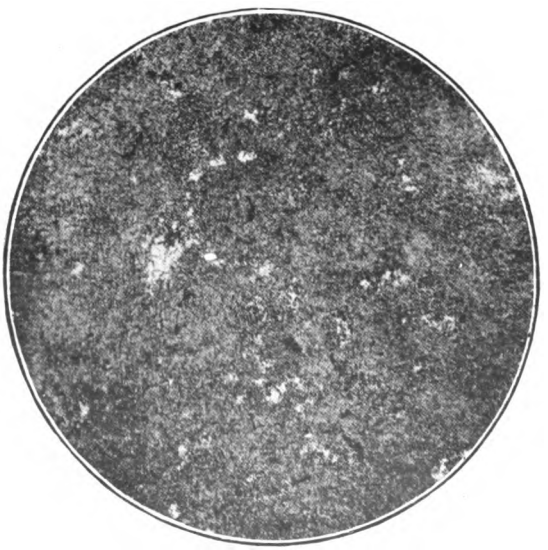

FIG. 9.—Peg quenched at 800° C. on heating. x 25.

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COMPLETE DIFFUSION.

In the peg withdrawn at 850° C. the diffusion was found to be complete (fig. 10). But the inter-diffusion of the two constituents has not only obliterated the original coarse outlines, along which a shock fracture between one crystal and the other could be easily led, it has also permitted the material as a whole to break up into a mass of much smaller crystals. The crystalline structure is now so fine that a magnification of twenty-five diameters, as used for all the previous photographs, gives no longer a useful idea of what

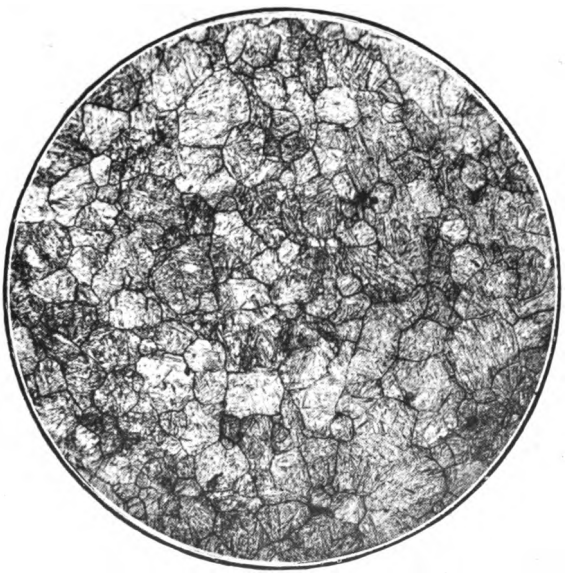

FIG. 10.—Peg quenched at 850° C. on heating. x 100.

is taking place, so that fig. 10 and the rest of this series were made at a magnification of at least four times greater.

On comparing the mean size of the crystalline grains in fig. 10 with the larger grains in the original structure, it is surprising to find to what extent the former have been disintegrated, as it were. In order to make the comparison easier, a part of fig. 5 has been magnified to the same extent as fig. 10, and a portion of the latter figure has been inserted within the former. In the area occupied by the large crystal there is sufficient room for four hundred of the average sized crystals existing in the refined material. But the photographs (fig. 11) deal with surfaces only, and not volumes.

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If, however, we assume that the third dimension of the crystal is of the same order as the two measurable dimensions, it is found by calculation that the approximate number of small crystals which have replaced the larger primary one is eight thousand.

It is perhaps not strictly true to say that the refining of an overheated steel is effected as soon as the pearlite, which becomes transformed always within its own areas at

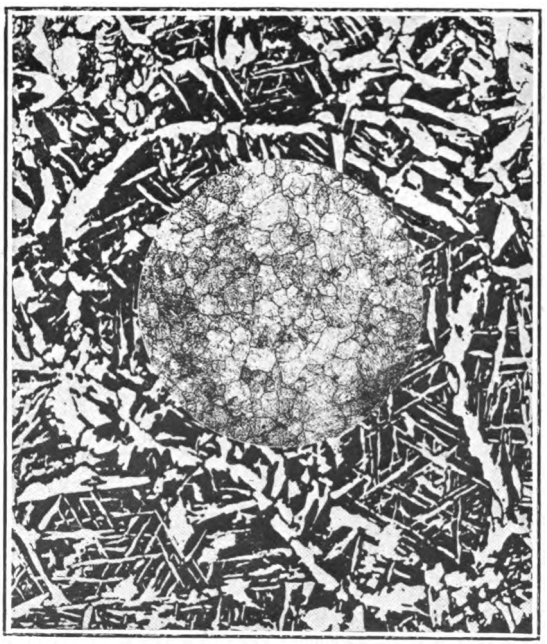

FIG. 11.—Figs. 5 and 10 both photographed at 100 diameters, and then reduced.

about 740° C., has inter-diffused completely with the free ferrite in low carbon steels or with the free cementite in high carbon steels, but it is certainly impossible to refine a steel satisfactorily unless the temperature has been at least sufficiently high to permit the inter-diffusion to occur completely. It is therefore of great practical importance to know what temperatures should be chosen for steels of varying composition, and on that account some space will be devoted later (page 77) to a graphic representation of such information known as the iron-carbon equilibrium diagram.

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CHANGES ON COOLING.

On pursuing the same method of observation during the cooling period, it is found that the completely diffused and apparently homogeneous material begins to reform distinct constituents as soon as the temperature falls to a certain figure which is constant for the same kind of steel. For the material under observation the highest temperature on cooling at which traces of free ferrite should be observable is 800° C., and we find as a matter of fact that the peg withdrawn and quenched at exactly 800° C. does show, here and there only, very small specks of ferrite: the photograph (fig. 12) has purposely been printed very dark so as to make the particles of ferrite more clearly visible.

FIG. 12.—Peg quenched at 800° C. on cooling. x 100.

As the temperature gradually decreases, more and more ferrite falls out of solution. The amount formed by the time 760° C. is reached is clearly shown in fig. 13, and at 740° C. the greater part of the ferrite has already been deposited (fig. 14). The amount increases until the temperature has fallen to about 680° C. At this moment the condition of the steel, but not the actual structural arrangement, is very much like it was during the heating operation, when the pearlite areas had undergone the transformation, but had not yet begun to diffuse into their adjacent con-

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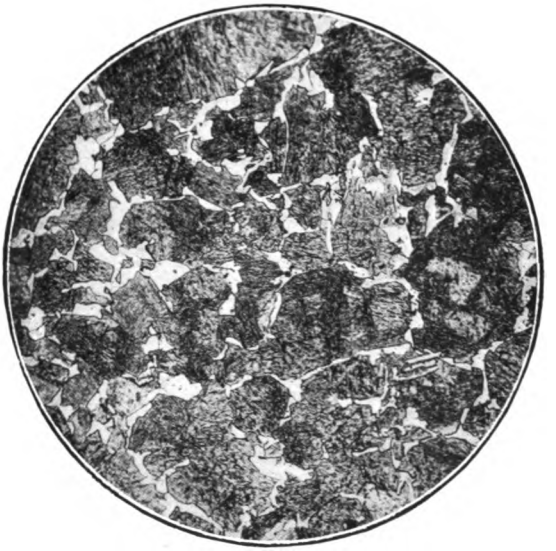

FIG. 13.—Peg quenched at 760° C. on cooling. x 100.

FIG. 14.—Peg quenched at 740° C. on cooling. x 100.

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stituent parts (figs. 5 and 7). The next peg was withdrawn at 670° C. after all the free ferrite had been already formed and just as the pearlite areas were in the act of assuming the original sandwich-like appearance. In fig. 15, made from the peg withdrawn at 670° C., the laminated structure of the pearlite already formed is seen side by side in the same patch with the unchanged solid solution, as it is called, and we thus see that during a fall of temperature extending over not more than 3° C. or 4° C., the steel passes from a state in which it may be made hard by quenching to a state in which it would remain quite soft in spite of the quenching.

FIG. 15.—Peg quenched at 670° C. on cooling. x 800.

After all the available free ferrite has been formed and the residual solid solution has dissociated into pearlite, then nothing more by way of structural change can occur. The microscopic appearance of the material has assumed the form shown in fig. 16, and remains unaltered in that form at whatever rate the subsequent cooling may take place. What has been accomplished during this excursion into the region of high temperatures and back again is brought out graphically by the two low power photographs in fig. 17, which were made from the same material before and after

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the refining treatment. This illustration may be taken to represent, broadly though not actually, the respective con-

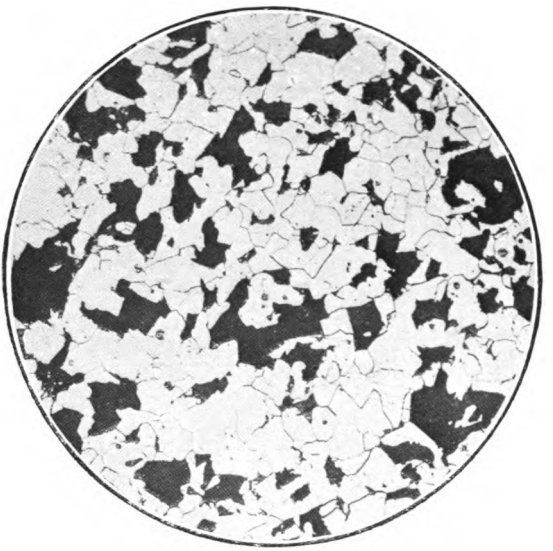

FIG. 16.—Any peg withdrawn below 670° C. on cooling. x 100.

ditions of the core of case-hardened objects which on the one hand have been quenched direct from the box, and on the

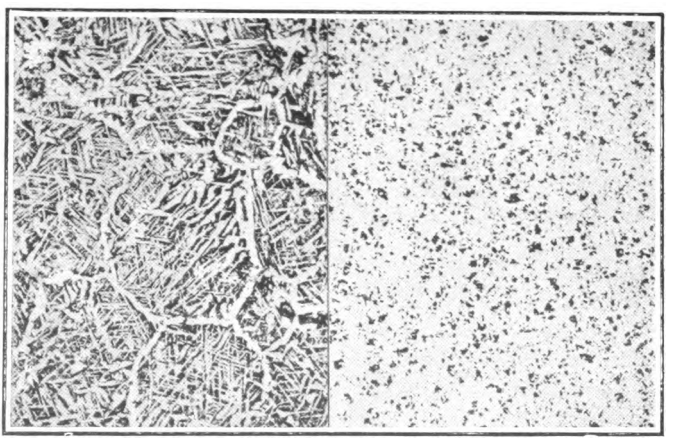

FIG. 17.—Overheated steel before and after refining.

other hand have been reheated to 900° C., cooled in the air, and again reheated for final quenching. The mechanical

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properties of bars after varied treatment and the appearances of their fractures will be dealt with later.

DOUBLE QUENCHING.

When case-hardened objects which have been already refined by reheating and air cooling are reheated to a lower temperature, say, 780° C., and quenched in order to harden the case, we know now what will happen to the core. The transformation in the pearlite areas will take place as the temperature rises through 750° C., and they will then diffuse somewhat, but not completely. The resulting structure will be fixed more or less, according to the thickness of the bars, etc., by the subsequent quenching, but there will be always a considerable amount of free ferrite to impart softness and toughness to the core.

But if the bar after the first reheating to the higher temperature, *i.e.*, until the constituents have inter-diffused completely, is quenched in water, instead of being allowed to cool in the air or otherwise, then the condition of the material before final quenching is quite different. It is just as truly refined, because all heat treatment applied to steel with the object of refining coarse structures—mechanical work being, of course, excepted—is operative only during the heating period, the difference in the rate of cooling as between air and water being of little or no consequence so far as the size of the crystalline grain is concerned. The difference, however, between specimens which have been quickly and slowly cooled from the high refining heat is of great consequence to the case-hardener whose aim it is to produce a hard case around a soft flexible core which, on being fractured, will have a grey fibrous-looking appearance. What those differences amount to can be adequately expressed only in terms of structures and associated mechanical properties. It is, therefore, necessary to revert to the only reliable method of asking and answering questions, viz., careful experiment and close observation.

What happens, then, if a piece of mild steel which has been already quenched to fix the constituents in the completely diffused state be again reheated to such temperatures as are employed in the final hardening of the carburised layer of case-hardened objects, and in what respects does the core of such objects differ both structurally and mechanically from the core of an object whose constituents are in the normal or undiffused state?

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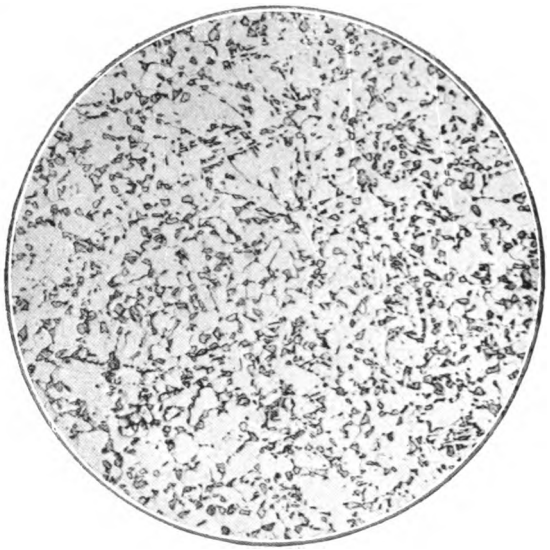

FIG. 18A.—Mild steel quenched from 800° C. after previous quenching from 920° C. x 200.

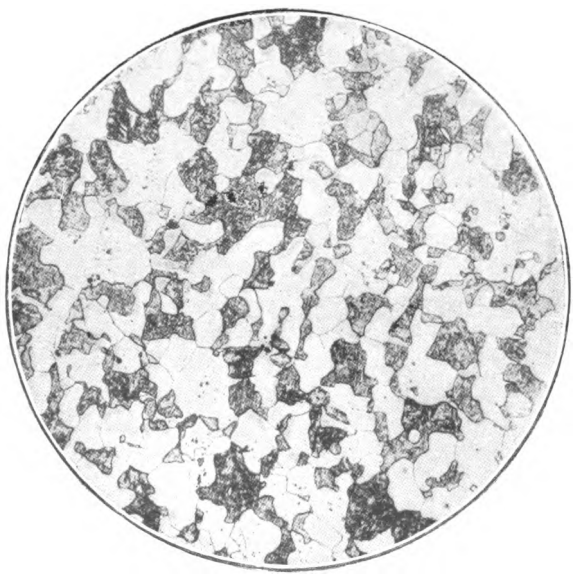

FIG 18B —Mild steel quenched from 800° C. after cooling slowly and reheating. x 100.

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The temperature employed for the final hardening of case-hardened objects must be at least 750° C., and is not allowed generally to exceed 800° C. In mild steels of the same ultimate chemical composition within or about a range of temperature between 750° C. and 800° C., it is possible to have represented three distinct conditions as follow:

(*a*) Material previously quenched from the completely diffused state.

(*b*) Material previously in the normal or annealed state.

(*c*) Material previously diffused and cooled only to the lower temperature.

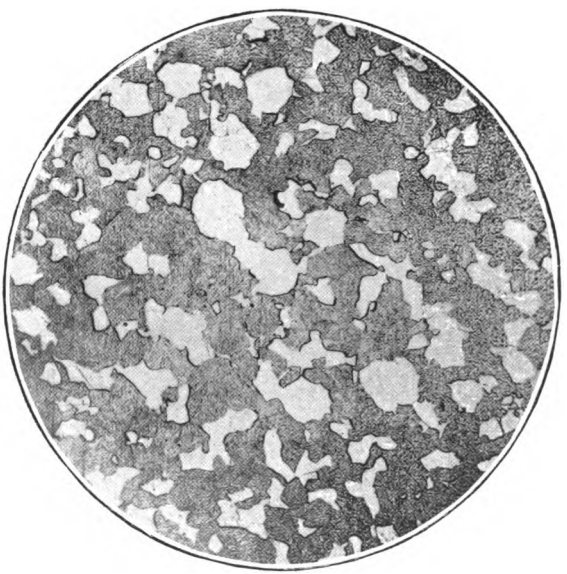

FIG. 18c.—Mild steel quenched from 800° C. after cooling to that temperature from 920° C. x 100.

For the purposes of observation pieces of case-hardening steel 1in. × $\frac{3}{8}$ × $\frac{3}{16}$in., containing .10 per cent. carbon and .25 per cent. manganese, were heated to 920° C. Pieces marked A were quenched in water, pieces marked B were cooled down to ordinary temperature in about two hours, and a piece marked C was at a temperature of 920° C. when, along with a piece each of A and B, it was placed in a furnace at 800° C. After being kept at 800° C. for one hour, the three pieces were quenched in water, and, after suitable

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preparation, photographed, with the result shown in figs. 18A, 18B, and 18C.

What is most strikingly illustrated by these photographs is the fact that the completely diffused and quenched material A does not again form significant patches of the two constituents on reheating for the final quenching operation. That the conpletely diffused (solid solution) areas do undergo a marked change when the hardening temperature is reached is undoubtedly true, but there is not the time, even if they had the disposition, during the course of one hour for the materials to dissociate and form afresh the comparatively large masses of ferrite which existed in the original material and exist also in figs. B and C. What happens to the A material during the reheating operation may be expressed in non-technical language as follows. The material gradually softens, as all hardened steel objects do on reheating, up to a temperature just short of that at which the possibility of hardening the normal steel occurs, say 740° C., and during this period some modification of what we know as pearlite is formed. At the hardening temperature, say 750° C., the modified pearlite diffuses within its own minute areas as the normal material did in figs. 6 and 7, and leaves the excess amount of free ferrite in an extremely fine state of division, disseminated with great uniformity and thoroughness throughout the mass of material. We thus have in each case (A, B, and C) a material made of a harder and softer constituent, and in each case also the general hardness is approximately the same, but in A these two constituents are of much smaller size and more thoroughly intermixed throughout the mass of the material. This explanation is not a complete one, nor is it free from certain elements of assumption, but it provides a working hypothesis for a difference between the doubly quenched and singly quenched materials to which the case-hardener attaches a great deal of importance, namely, the greater tendency of double-quenched material to fracture with a fibrous core.

When the final quenching temperature is below 800° C., as it usually is, then changes of like kind but more favourable still to the double-quenched material will occur. It is not necessary to reproduce the structure of similar series of observations made at 700° C. and 760° C. in the same way as the ones with a quenching temperature of 800° C. were made: but it is of some importance to point out that the

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doubly quenched steel, in addition to enhanced shock-resisting properties, is also stronger, *i.e.*, relatively harder. In support of this contention, the relative hardness of the small treated pieces as determined by the Brinell machine with a ball 10 mm. in diameter under a load of 1,000 kgs. is given in the following table :

Previous Treatment.	Diameter of Impression after finally Quenching from		
	700° C.	760° C.	800° C.
	mm.	mm.	mm.
A.—Water-quenched from 920° C. . .	3·5	3·4	3·05
B.—Cooled in 2 hrs. from 920° C. . .	3·8	3·5	3·3

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III.

FIBRE AND LAMINATION IN THE CORE.

A FIBROUS core may be obtainable in case-hardened wrought iron if it is quenched direct from the cementing box, but a quickly made fracture will always expose a crystalline appearance in a mild steel object which has been treated in the same manner. This does not mean that the one material is an aggregation of crystals and the other is not; both, of course, are crystalline in the sense that they are composed of crystalline grains, as are all metals. It does not even mean that the crystals in the one case are smaller than they are in the other, though as a rule, other things being equal, the material having the smaller crystals is more apt to break with a grey fibrous fracture.

WHAT IS FIBRE?

A crystalline fracture means an inter-crystalline fracture, *i.e.*, the material has separated into two or more pieces along the junctions between the crystals. On the other hand, in the fibrous material the cohesion between the crystals has been stronger than the crystals themselves, and under the effort to separate them they have distorted and elongated, and ultimately present a mass of rugged broken ends of a grey colour which has the appearance of fibre. Every mechanic knows that a piece of mild steel made sufficiently thin and humoured in the breaking can be made to expose a fibrous fracture, whereas the toughest of wrought iron would probably exhibit a crystalline fracture if broken appropriately and with sufficient rapidity. The distinction between a crystalline and fibrous fracture may be illustrated by a number of individuals with joined hands. They may grip each other so loosely that a certain effort pulls their hands apart—they may grip so firmly that some one or other joint is dislocated and muscles torn before the hand hold loosens: this latter case is akin to a fibrous fracture.

That a case-hardened object in general should break with a fibrous fracture is undoubtedly desirable, but it is not always essential, and more, indeed, may be paid for the fibrous appearance than it is actually worth. If it be admitted that the "fibrous" fractures are due to a defor-

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mation of the crystals themselves by a lesser effort than would be required to separate the crystals from each other then obviously a fibrous fracture may be ensured in either of two ways.

(1.) By increasing the inter-crystalline cohesion.

(2.) By decreasing the strength of the crystals themselves.

And there are means whereby the former purpose may be accomplished, even on very coarsely crystalline material, without deteriorating the strength of the crystal itself. Such means, however, cannot be usefully applied to case-hardened objects.

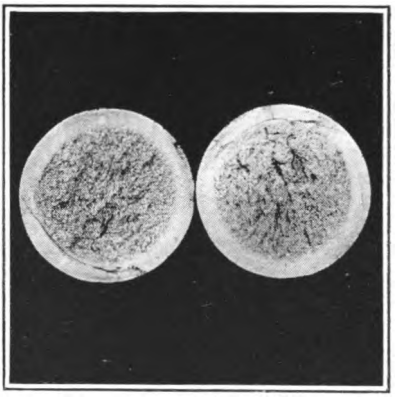

FIG. 19.—Fine crystalline core in case-hardened bar.

But there are purposes for which very mild steels with fibred cores are not so suitable as a harder steel in which it may be impossible, under manufacturing conditions, to produce fibre. Ball races, and such articles as have to withstand a heavy crushing load and at the same time preserve a continuous and unsplintered surface, are the most noteworthy instances. In some of the Continental factories such articles are made from high carbon steels, and sometimes even from chromium steels, which are hardened without being cemented; but in England the races are generally, though not invariably, made from case-hardened steel, and the finished articles have a fine crystalline core, which is specially adapted to resist heavy crushing loads, *i.e.*, the crystal itself is made very strong that it may not yield under heavy loads. The fracture of such objects is very much like that illustrated in fig. 19.

FIBROUS CORES.

Quite apart from the contention in the last paragraph, there is the question of whether the core of a case-hardened object made from a particular kind of mild steel shall be made fibrous or allowed to remain crystalline. If the former is desired then it can be secured by double quenching more certainly than in any other way. It cannot be secured at all

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if the articles are quenched direct from the cementing furnace, because under such conditions the crystalline structure is large and the crystals themselves are comparatively hard, and both these circumstances, as we have seen, are favourable to inter-crystalline fracture. If after the refining heat the objects are air-cooled, it may be possible to produce a fibrous fracture because the crystalline structure is small. But if the objects are water quenched from the refining heat, the conditions are most favourable, because, in addition to being small, the crystals have also the internal structure of hardened and tempered steel, and are more homogeneous than those cooled more slowly from the refining heat, as is seen by observation of figs. 18A, 18B, and 18C.

Just as air-cooling from the refining heat is less favourable to the production of fibred cores than is water quenching, so oil quenching also is less effective than water for the purpose, because its cooling effect is less rapid, and it does not preserve the constituents of the steel so completely in the inter-diffused state. But oil is frequently used if it effects the desired purpose, as it causes less warping in the object and less danger of cracks and splintering in the case.

FINAL QUENCHING.

Whilst being reheated for the final hardening, the core becomes softer and softer as the temperature rises; and attains the maximum degree of toughness and softness after water quenching from a temperature between 720° C. and 740° C. The ideal condition for the production of fibrous cores would be attained if the casing could be effectively hardened from this range of temperature, but it cannot. Any temperature from which quenching will confer hardness on the cemented case will also confer some degree of hardness on the core, because the pearlite areas in low carbon steel are transformed into the hardenable state at about the same temperature, as a like change occurs in high carbon steel which contains an equal amount of manganese, etc. It may occasionally be practicable to heat the casing to the hardening temperature so quickly that the temperature of the core lags appreciably behind it, just as the teeth of taps and reamers may be hardened without hardening the main body of the tool: but such practices are only of limited application, and rarely commendable (*see page* 164).

What should, however, be aimed at is to use the lowest temperature at which the case can be brought to the desired degree of hardness without risking the formation of soft

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spots, as under such circumstances the core will be hardened only to a minimal extent, and hardly at all in thick objects. When thin objects are being dealt with, the desired purpose is assisted either by using steel which is as low as possible in carbon and manganese, or by quenching in oil instead of water. The fractures in fig. 20 were made from portions of the same case-hardened bar after quenching from the same temperature in water (right) and in oil (left). These remarks about quenching temperatures apply also, of course, to cores of case-hardened objects in general, which are kept as soft as possible, whether they are intended to be "fibrous" or not.

FIBRE STEELS.

It has been said that many manufacturers of case-hardened articles attach an unmerited value to the appearance of fibre in fractured surfaces, and especially in demanding that the fracture shall have the torn and reedy appearance to be seen at its best in the fractured surfaces of wrought-iron bars. There can be no question that the short, grey-looking fracture indicates toughness, and is worth the labour of producing, if it involves no actual disadvantage in other respects. But it should be clearly distinguished from lamination, which heightens the appearance of fibre, and may or may not be advantageous to the behaviour of the core, and is always more or less disadvantageous to the behaviour of the casing. The lamination referred to is due to imperfect continuity in the bar caused by spongy ingots having been imperfectly welded in the hammering or rolling operation, or by the occlusion of slag which has been drawn out with the bar into streaks. Where the streakiness is due to occluded slag, and, besides being incidental to the mode of manufacture, is supposed to be a virtue, as in shear steel, it has been found possible to simulate its appearance by casting spongy ingots.

FIG. 20.—Fractures of bars quenched in water (right) and oil (left).

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But does the case-hardener want either seams or slag streaks, and is he prepared to put up with them in the hardened case as well as utilise them in the soft core? The presence of numerous slag streaks of visible dimensions is unavoidably associated with the mode of manufacturing wrought-iron. They are but the remnant of slag which could not be squeezed from the puddled bar. They are the main distinction between dead mild steel and wrought-iron, and their presence explains why wrought-iron is more highly prized than ingot iron or mild steel for the camshafts of quartz crushing stamps and other objects exposed to very great transverse shocks and distortion.

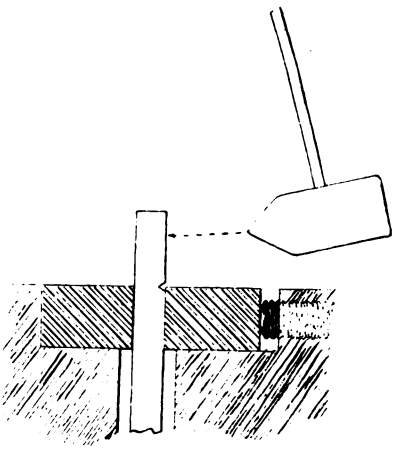

FIG. 21.—Diagrammatic representation of impact tests.

If use be made of a suitable piece of apparatus, say an impact testing machine such as is represented diagrammatically in fig. 21, for measuring the energy required to break a

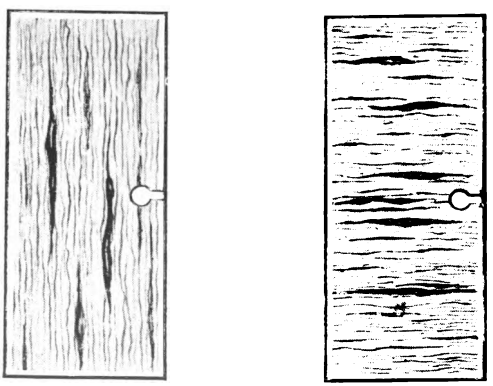

FIG. 22.—Showing how seams, etc., affect resistance to fracture.

notched bar, it will be found that the impact figures are abnormally great material containing when slag streaks or seams is broken by a blow delivered at right angles to the

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direction of the streaks, whereas the impact figures are abnormally small when the blow is delivered in a direction parallel to the streaks, as indicated respectively by A and B in fig. 22. The following are a few typical figures relating to very varied kinds of material, which indicate the relative strength of the material when stressed by shock along and across the direction of rolling. The tests were made in triplicate :

Kind of Steel.	Impact Figures in ft. lbs.					
	Across Direction.			Parallel to Direction.		
Nickel chrome steel	81	84	83	30	25	35
Nickel steel	56	61	58	17	21	24
Finished waggon spring ..	36	35	39	8	7	9
Titanium steel	25	26	27	6	5	5
Special case-hardening steel	98	104	106	32	43	37

TRANSVERSE CRACKS.

The effort required to force a fracture across a bar of streaky iron or steel is greater than the effort which would be required to force a fracture across material of the same kind free from slag streaks or seams. Accepting the photograph reproduced in fig. 23 as a representation of a notched bar, it is clear that the crack already started from the bottom of the notch could be extended through the bar by a certain definite effort if the material were homogeneous. When, however, the crack in its course reaches the slag streak, the bar has been already bent through a greater or less angle, and the bending force is no longer acting strictly parallel to the direction of the crack. This means that part of the bending effort tends to divert the crack, *via* the slag streak, parallel to the length of the bar, and so much effort is entirely lost as far as the original purpose of breaking the bar across is concerned. Moreover, before that portion of the crack under consideration can continue along the intended path, *i.e.*, across the bar, it has to make a fresh start, and must distort the material in its immediate neighbourhood until a new crack is formed. Now, everyone knows as a matter of experience that it is more troublesome to distort soft material into an initial crack than it is to continue a crack

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which has been already started. It is, therefore, not difficult to realise why the occurrence of streaks and seams in a bar of iron or mild steel increases the effort required to propagate a crack across it. It should also be frankly admitted that from this particular point of view the seams or slag streaks are of value. But it must also be realised and admitted with equal frankness that to crack the bar along the direction of rolling will be proportionately easy.

LAMINATION.

Lamination in wrought iron, as disclosed by fractures made across the direction of rolling or hammering, follows inevitably from the presence of occluded slag streaks. The manner in which the lamination develops may be illustrated by making a V notch on the edge of a sheet of note-paper

FIG. 23.—Wrought iron containing slag streaks. x 150.

which has been streaked along its length with the point of a sharp knife. When the paper is taken with the thumb and finger on either side of the notch and an effort is made to tear it across, the tear will branch off at right angles along the first deeply streaked line, and the tear will follow a very irregular path before reaching the opposite edge of the note-paper. It is in the same way by reason of transverse weakness, due to a cold drawing operation, that hard steel wire such as is used for colliery ropes will break at an oblique angle when notched and bent, though this case may be nothing more than an example of partial cleavage, as in slates, due to pressure exerted at right angles to the subsequent cleavage planes.

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Slag is an unavoidable constituent of steel made in large masses. It may therefore be said to exist in all commercial case-hardening steels in greater or less amount. If the streaks into which the slag globules existing in the cast ingot have been elongated are large and numerous, as they are in wrought iron, the fracture may be as laminated as the case-hardened specimens represented by the fig. 24. They may, however, be equally numerous, but so small as not to cause marked lamination, and yet large enough to produce innumerable minute laminations which heighten the appreciated appearance of fibre in the fractured surfaces. SLAG STREAKS.

Well disseminated slag streaks of small dimensions are favourable to the production of fibre for another reason.

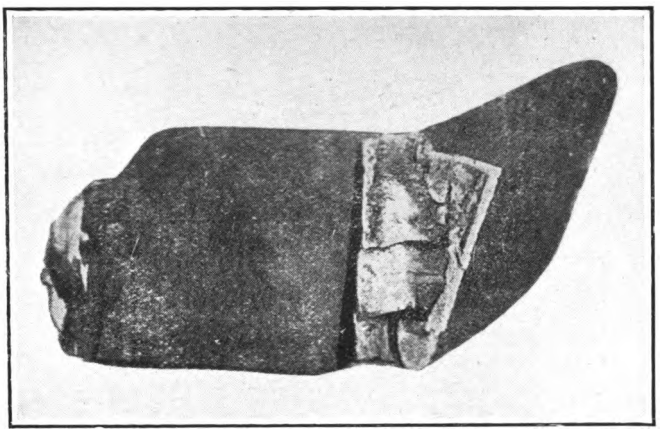

FIG. 24.—Laminated fracture in case-hardened wrought iron.

As small globules in the cooling ingot and as streaks in the billets or rolled bars, they have the power of attracting to themselves the free ferrite as it falls out of solution, just as threads suspended in syrup act as nuclei for the clusters of crystals known as sugar candy.* Fig. 25 shows a large globule of slag in its ferrite envelope as it exists in the ingot, and fig. 26 shows a number of elongated ferrite envelopes, each of which encloses a slag streak or a string of short

* Thorpe's dictionary says: "If a sugar solution be very slowly evaporated, large crystals of sugar candy are obtained. To assist in the formation of these, it is usual to have threads dipping into the syrup to act as nuclei."

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FIG. 25.—Slag globule in ferrite envelope. x 50.

FIG. 26.—Slag streaks in ferrite bands. x 50.

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streaks which have been elongated with the steel during the rolling or forging operation. When material of this kind has to be broken at right angles to the length of the ferrite bands, the crack has to make its way through layers of material which are relatively hard and soft, and are at the same time large enough to deflect and distort as two separate substances; this also, in addition to the effect of the slag, disturbs the even progress of a crack, and heightens the appearance of fibre.

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IV.

PROPERTIES AND DEFECTS OF HARDENED CASES.

THE failure of hardened steel objects during or prior to use is rarely caused by any one simple and well-defined cause. With an altered design the material used would have made an efficient object; if a different material had been used the accepted design would not have been objectionable. Also some degree of overheating and careless quenching may be negligible or lead to disastrous results, according to the prevailing conditions with which they are associated. It is quite possible, therefore, to find numerous examples which appear to be exceptions to the general statement that free cementite in case-hardened articles is objectionable.

FREE CEMENTITE.

The presence of free cementite in commercially produced objects is due to the casing operation having been conducted at too high a temperature; and in extreme instances it may be detected along the edges and especially about the corners of a fractured surface, to which it gives a very coarse and markedly crystalline appearance (see the upper edge of fig. 27, and fig. 28); when the fracture is examined by means of a hand lens the separate crystalline grains stand out with great distinctness. If the case-hardened object is required to withstand a vigorous rubbing or rolling action without shock its surface will wear all the better for containing free cementite when it has once been smoothly finished and got safely into use. But it should be remembered that cementite is an extremely hard and brittle substance existing in the steel in a pattern very much like the appearance of crazy glass; and also that it exists in the greatest amount and the most dangerous condition in those parts of the object —*i.e.*, corners and edges—which are most exposed to destructive stresses during quenching.

Free cementite has not the same coefficient of expansion as the material in which it lies embedded, and its occurrence is on this account very favourable to both the origin and extension of cracks. The dark outlines in fig. 29, made from

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a case-hardened object, are free cementite (made visible by boiling the polished specimen in a solution of sodium picrate), and the path of the obvious crack is seen to be coincident with the cementite outlines.

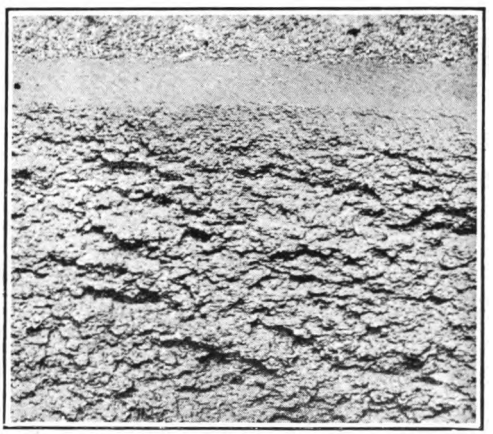

FIG. 27.—Coarse crystalline appearance of fracture due to free cementite.

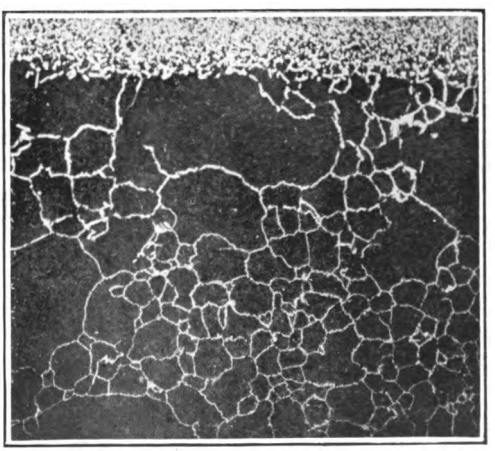

FIG. 28.—Micro-photograph of extreme edge of fig. 27. x 25.

REFINING THE CASE.

When material containing free cementite has been allowed to cool in the cementing box it has a coarse overheated structure, not only in the core, as explained in a previous

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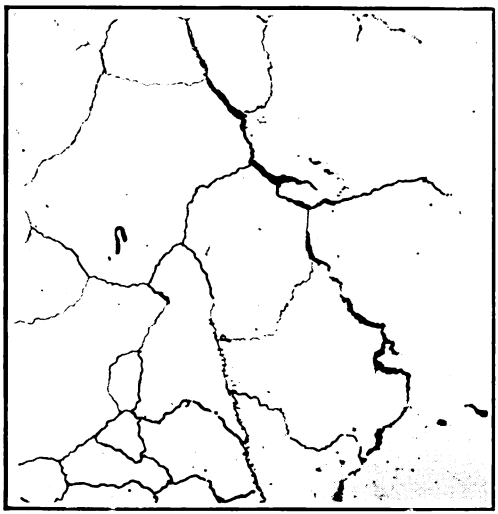

FIG. 29.—Crack proceeding along cementite outlines. x 100.

chapter, but also in the case. And just as no effective refining of the structure can take place in the core until it has been reheated to a temperature at which the pearlite areas inter-diffuse completely with the ferrite, so also, on the other hand, it is impossible to refine the outermost layers of the case until all the pearlite and free cementite which they may contain have completely diffused into each other. Because this condition has not been complied with it is by no means uncommon to observe a coarser structure about the corners than in any other part of a fractured case. Free cementite, if sufficient in amount, will form complete envelopes around the crystalline grains, and the size of those grains will correspond to the degree of overheating attained in the cementing operation. Any reheating temperature which is not sufficiently high to cause complete diffusion of the cementite envelopes will leave the size of the crystalline structures unchanged.

The minimum temperature required to refine coarsely crystalline material which contains free cementite depends on the amount of carbon present in that part of the casing in which it exists. The greater the amount of carbon, the higher the refining temperature must be. The relation between these two variables is discussed on page 79;

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but at present it may be said that on effective and long-continued cementation the amount of carbon will be governed by the temperature used and be some indication of the maximum temperature attained, *i.e.*, if the carbon on the extreme face is 1.5 per cent., the temperature must have been at least 950° C., and a temperature equally as high as that at which the carbon was introduced must be used to refine effectively the structure outlined by the cementite envelopes.

Where the practice of a preliminary quenching from a high temperature in order to refine the core is adopted, it is fairly safe to assume that all the free cementite will inter-

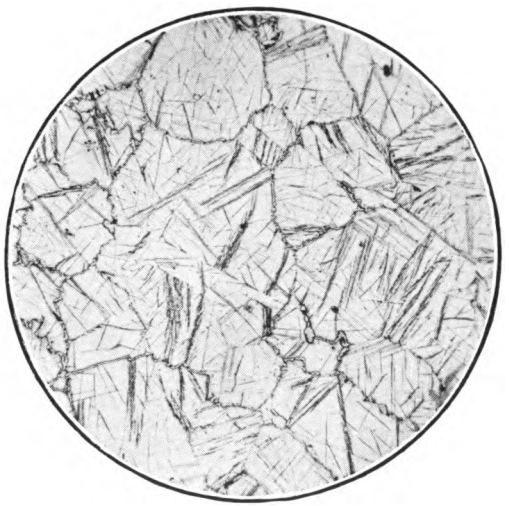

FIG. 30.—Cementite in needles and cell walls in quenched specimen. x 300.

diffuse completely with its adjacent pearlite if the carbon does not exceed 1.30 per cent., which allows for a liberal margin of error in the cementing temperature. During this operation a portion of the cementite will be fixed in the diffused state, and the remainder will fall out again as cell walls of smaller dimensions and in a needle-like form or in both states, as exemplified by fig. 30. In this more attenuated form the cementite is less favourable to the formation and extension of cracks, but its presence in any

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form whatever decreases the safety with which the first high temperature quenching operation can be used.

When the occurrence of free cementite is intentional the circumstances are generally such that it does not greatly matter whether the core of the object is made fibrous or not, and the high temperature quenching treatment, with its attendant dangers, may then be omitted; or in certain special objects, such as armour plates, the soft portions are made fibrous beforehand and kept cool during the final reheating and quenching of the cemented face. But so far as the bulk of case-hardening work is concerned, the most satisfactory attitude towards free cementite is to keep it out of the casing altogether, and this can be done most easily by controlling the temperature of cementation.

SUPER-CARBURISATION.

When the carburisation is required to extend deeply—say 5 mm. or more — then unusually high temperatures are essential; the penetration is not attainable otherwise. This means that the rate at which carbon is taken up by the surface is also increased and the formation of free cementite is unavoidable. If the actual carburisation of the surface could be limited as the temperature rises, then deep penetration without supercarburisation would occur, but it is impracticable to adjust industrial operations to such requirements.

If, however, an object which has been already deeply cemented is heated again to a high temperature in an atmosphere which is certainly non-oxidising and not appreciably carburising, then the free cementite formed already will diffuse inwards, the carburised layer will increase in thickness, and the hardened objects when broken will exhibit less sign or no sign of "freckled corners." These facts may be illustrated by the following example:

A piece of steel was cemented (by Portevin and Beriot) for eight hours at 1,000° C., and on measuring up the cemented case it was found to consist of—

1.2 mm., containing more than .9 per cent. carbon (hypereutectoid).

0.9 mm., containing about .9 per cent. carbon (eutectoid).

1.1 mm., containing less than .9 per cent. carbon (hypoeutectoid).

Portions of the bar were then heated for varying lengths of time at 1,000° C. in a non-oxidising atmosphere, and, after

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preparing, polished and etched sections were found to have cemented cases consisting of :

Time Heating.	Hyper-eutectoid.	Eutectoid.	Hyper-eutect.	TOTAL.
	mm.	mm.	mm.	mm.
As cemented ..	1.20	.9	1.1	3.2
5 hours ..	.0	2.3	2.0	4.3
15 hours ..	.0	2.4	3.2	5.6
30 hours ..	.0	3.0	>6.6	>10.0

A pictorial representation of the same phenomena is seen in fig. 31A and fig. 31B. These comparative figures show clearly the deepening of the cemented layer, and also the thinning of the free cementite envelopes.

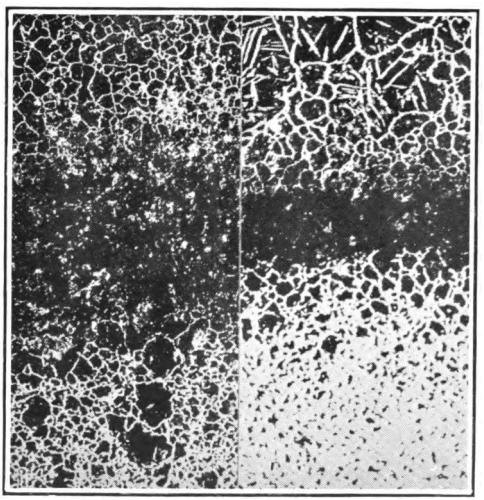

FIG. 31B. FIG. 31A.

FIG. 31A.—Bar cemented at 1,050° C. for eight hours. x 25.
FIG. 31B.—Same bar as 31A reheated twelve hours at 1,000° C. x 25.

The substance of the last two paragraphs illustrates the steps which may be taken to ensure either a highly carburised surface tapering off quickly to the normal carbon of the steel or a casing which changes less suddenly in carbon

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content from the surface inwards. To prepare the former the cementation should be carried out at a relatively high temperature: to prepare the latter a lower temperature and a longer time are desirable. Also, of course, a deeper and more uniform casing can be obtained by first cementing for a short time at a high temperature and then reheating, as indicated, out of contact with a carburising reagent.

SLAG STREAKS.

What has been already said about the origin of cracks owing to the presence of free cementite applies also to incidental slag occlusions, though the trouble on the one hand must be shouldered by the case-hardener and is avoidable, whereas the steel maker is responsible for the slag streaks, and they are to some extent unavoidable. It is, however, much easier to blame the steel maker when the hardened surfaces crack and flake off than to make a careful investigation which may locate the blame elsewhere.

It is in the form of a less durable case that the case-hardener may have to pay for his insistence on fibrous-looking cores which are tough and have other properties akin to wrought iron (see fig. 24). There are possibly purposes which are served just as well by case-hardened objects whether the casing contains slag streaks or not, just as there are purposes which are not affected at all by the presence of free cementite; but it is as well, if trouble should arise, to know the causes to which it may be ascribed. The longer or shorter black lines which may be observed in case-hardened spindles of grinding machines, etc., owe their origin most frequently to minute streaks of slag which as surface defects have extended under the influence of the hardening stresses. In ball races also a slag streak quite imperceptible to the untrained eye will cause extensive splintering. As the balls move in the race they are barely affected by the embedded impurity, but the slag streak being brittle and not strongly coherent to the steel, is dislodged sooner or later, and the small irregularity thus formed causes the balls to jump, at first imperceptibly, as they pass over it. Later, however, the jolt of the balls breaks down the hard edges which have outlined the slag streak, and in course of time the cavity becomes splintered into measurable dimensions, and both race and balls are spoiled.

Balls are not generally made from case-hardened steel, but they do sometimes contain streaks, incidental to certain ways of manufacturing crucible steel, which, though not

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slag, behave in some ways as if they were. Such balls may flake in concentric circles, but more often than not they flake along lines roughly parallel to each other. When a ball is sectioned in a plane parallel to these lines, it is almost invariably found that the plane thus made lies in the length of the original bar of steel.

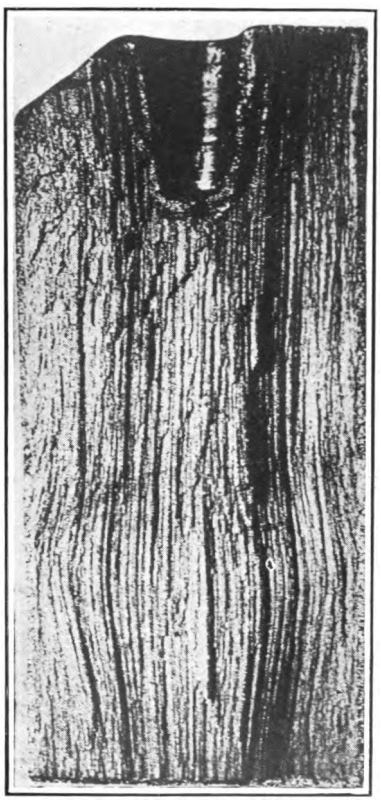

FIG. 32.—Fibrous fracture along length of case-hardened die.

HARMFUL FIBRE.

The slag streak is most deleterious in the case, and also in the core of a case-hardened object, when the stress it is intended to withstand tends to split the object along the directions in which it has been extended in the forging. Cut gears, for example, are stronger if made from forged discs than if made from discs which have been sawn off a forged bar, the difference in the two cases being dependent on the direction of stress in relation to the direction in which the slag streak lies. It is obvious also that for similar reasons a material might be quite satisfactory in the form of case-hardened piston pins, and very disappointing when used for the manufacture of drop-forged gears. The photograph reproduced in fig. 26 was made from a broken tooth of a case-hardened gear wheel. The long ferrite bands enclosing the slag streaks lay along the length of the tooth. Under the first serious stress every tooth in the wheel stripped off, and the fractures exhibited were very reedy, and might have been truly described as fibrous; but the fibre was lying in the wrong direction.

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Fig. 32 represents the fractured surface of a case-hardened die, used for forming nail or rivet heads. Clearly, the material in use would be stressed in a direction at right angles to the length of the bar, from which the die was made; in that direction, purely on account of what might be called the fibrous structure, the die was very weak. Such material in the soft core may be compared with a piece of cane; but the small seams or slag streaks in the hardened case are somewhat akin to a flaw in glass, and lead readily to destruction.

SOFT SPOTS.

Amongst the troubles associated with case-hardening, soft spots are not the least annoying. They may occur on the surface of the quenched objects, owing either to an insufficient temperature having been attained in the re-heating furnace or to the temperature having been depressed locally in transit between the furnace and the quenching tank. The precise reason for the latter cause may be handling with cold or wet tongs, contact with an unevenly heated furnace bottom, accidental splashing of water or momentary contact with some colder surface during transit to the hardening tank. The soft places are detectable with a file however they arise, but it is not possible by means of a file to determine whether the soft places have arisen because they have never been heated to the proper hardening temperature, or because the temperature prior to quenching has been locally depressed in an accidental manner.

It is possible, however, to distinguish between soft places which originate in either of the following ways:

(1.) Because the minimum hardening temperature has not been reached in the reheating furnace.

(2.) Because the temperature has been locally depressed or the quenching liquid has not cooled the object uniformly.

If, in the former case, the brightened object be immersed in a solution of alcohol or unmineralised methylated spirit to which two per cent. by volume of nitric acid (s.g. 1.42) has been added, the soft spots will become rather lighter in colour than the hard surrounding portions. But if either condition mentioned in the second case has prevailed, then the soft areas darken very quickly when brought into contact with the acidified spirit. A very good example of a case-hardened ring which was found to be soft after quenching is reproduced in fig. 33. The ring was found to be soft in

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unusual places when tested with a file, but the dark outline which appeared immediately on etching the brightened ring disclosed, not only the exact location of the soft places, but

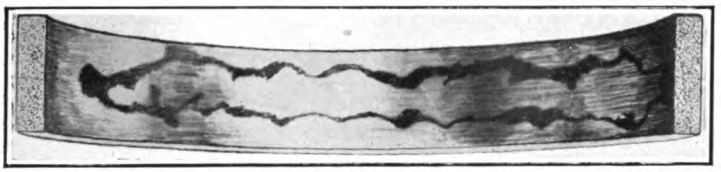

FIG. 33.—Dark-etching outline indicating soft part.

indicated also that the trouble was due neither to insufficient heating nor accidental cooling, but to want of uniform and rapid quenching in the hardening tank.

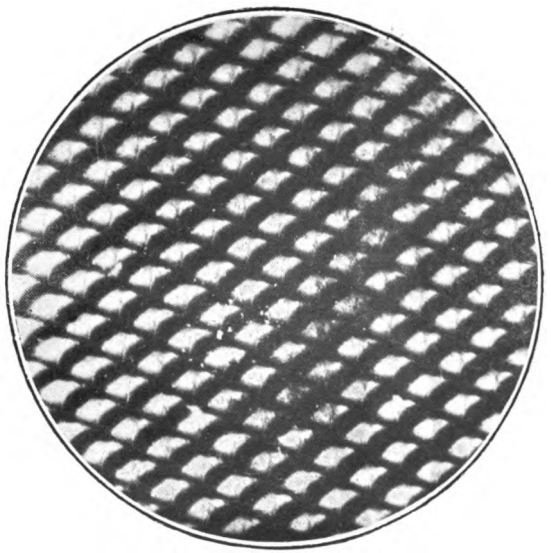

FIG. 33A. Troostite in hardened file (Stead).

TROOSTITE. No available magnification enables the microscope to discover in the dark outline of fig. 33 anything but a dark etching structureless substance. When steel cools very slowly from the hardenable condition, the pearlite laminæ formed are always visible at a magnification of two or three hundred diameters (see fig. 15), but the more rapidly the steel cools through the hardening range of temperature the less clearly defined the pearlite becomes; and ultimately when the rate of quenching is merely retarded in the hardening range suppression of the usual pearlite formation

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appears to be complete, and the laminæ, if they exist at all, are ultra-microscopic, *i.e.*, immeasurably small. When the steel occupies this midway condition it etches quickly with a very dark colouration, and the darkened area in this state is known as troostite. These conditions of cooling must exist at some point between the extreme surface and interior of most case-hardened bars, and dark-etching patches to correspond can usually be found on grinding, polishing and etching a transverse section.

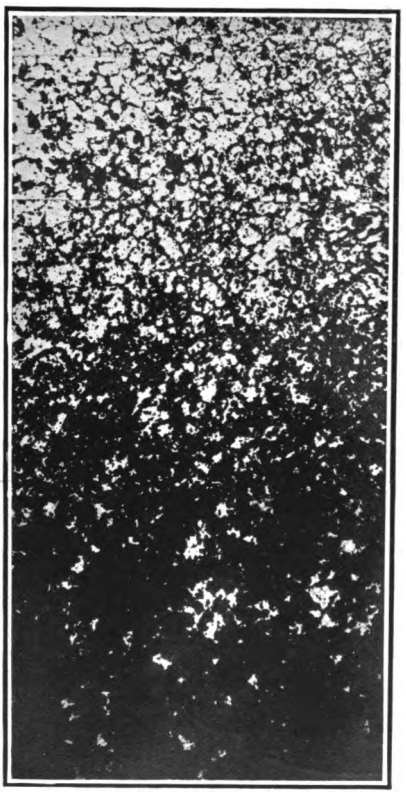

FIG. 34.—Troostite fringe on the edge of soft spots. x 200.

During the hardening of files the edges of the teeth cool very rapidly because they are small and the water completely surrounds them ; the heat is also quickly carried off from that part of the file immediately beneath each tooth to which the water cannot gain direct access. But the space between the teeth is partly filled by a paste to prevent lead, from the lead-heating bath, sticking in the teeth. In the small space covered by a few teeth we have material which is more quickly and less quickly quenched with the production in the latter case of well-defined strips of troostite. This enables us to produce a striking illustration of troostite as a micro-constituent of steel (fig. 33A), and provides also an example of the conditions favourable to its formation.

In the investigation of objectionable features such as soft patches it is sometimes necessary to allocate the responsibility for them to one operation or another or to one department or another in a manufacturing concern. How-

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ever delicately the decision may be expressed, it should be supported by the most conclusive evidence obtainable. On this account it may be usefully observed that the rapidity with which the soft patches etch black, the general shape

FIG. 35.—Troostite fringes within the core. x 200.

in which they occur, and most of all the way they lighten in tint on the edges and form a cellular fringe which is clearly visible under the microscope, are indications which do not occur simultaneously in soft patches unless they are caused by imperfect quenching. The cellular dark-etching fringe referred to is illustrated by fig. 34. Fringes of a similar kind occurring about the edges of transformed pearlite areas in the core of a case-hardened bar are reproduced in fig. 35.

GRINDING.

Soft patches may also be due to decarburisation of the surface during the reheating operation, or to the cementation having failed locally for some reason or another. The first-named is an infrequent occurrence, though, of course, careless reheating in an oxidising atmosphere may cause the entire surface to be soft ; and one hears of the second as an excuse which is frequently made and rarely confirmed. But in all cases where lack of sufficient carbon is the cause, the soft patches remain soft after the object has been rehardened, whereas soft patches, due to imperfect quenching or to the frictional heat of grinding, become hard again.

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Soft patches may originate very easily, and actually do originate very frequently, in the grinding operation. If a small object, such as a piston pin, be ground with a dry emery wheel, it becomes too hot to handle, and is soft over the entire surface. The frictional heat generated between the pin and the wheel is dissipated mainly as :

(1.) Sparks.
(2.) In the current of air due to the revolving wheel.
(3.) In the pin itself.

It is well known that the sparks are particles of metal torn or cut from the steel with so sudden a violence that the particles are raised to incandescence, and actually melt during their swift passage through the air.* It is therefore not difficult to realise that the hardened surface of the pin is softened locally, and seriatim during the contact between the wheel and the pin, and not merely or appreciably by that portion of the total heat generated which is diffused through the mass of the pin. It is found, moreover, that a soft patch purposely produced by rash grinding is much harder underneath than on the surface, which could be so only if the softening occurred as suggested at the moment of contact between the hard surface and the wheel.

* If a shower of sparks from an emery wheel is allowed to strike a glass plate, a certain number stick. These have two different forms : The first are rounded blobs, which suggest molten material ; and the second are curled pieces of metal, similar to steel filings (fig. 36). When revolving at a high speed, an emery wheel removes minute portions of metal, and whirls them quickly through the atmosphere. In the case of pure iron the oxidising mass ultimately fuses, and forms a pear-shaped tail at the end of the incandescent ray. In the presence of carbon, however, which is readily oxidisable, the oxidised envelope of the molten bead reacts violently with it, and produces a comparatively large volume of carbon dioxide gas, which, in escaping from the bead, breaks it up into radiating lines. As the speed of the reaction between the oxidised iron and the carbon of the steel, and also the amount of gas formed, depend on the carbon content of the steel, the explosive sparks produced under like conditions should vary in number or degree with the amount of carbon in the steel, and may serve as a rough indication of the amount of carbon present in a sample of steel. It has been claimed that the spark enables steels to be distinguished, which vary amongst themselves by less than .05 per cent. carbon. This seems an extravagant demand to make on a test which is exposed to a number of unavoidable variations in shop practice. It may, however, safely be said that the sparks given by wrought iron, mild steel, and high carbon steel, are sufficiently distinctive to be recognised and used for placing unknown materials into these groups and for settling with little trouble such questions as to whether an article is all steel or welded, whether or not it is case-hardened, and roughly to what extent and depth it has been case-hardened.

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It follows from the foregoing that, however bulky an object may be, or however copious a supply of water may be available, the production of soft patches on grinding will need to be carefully avoided. The following are useful precautions :

(1.) The operator must realise that it is possible to produce soft spots by grinding.

(2.) The wheel should cut freely.

(3.) The feed should be automatic and consistent with such conditions of cooling, etc., as experiment shows do not result in the production of soft spots.

(4.) The wheel should be dressed frequently, and the particular object ground immediately before dressing should be carefully examined.

(5.) Special vigilance should be exercised when a new wheel is put into use.

(6.) Objects should be kept as straight as possible in hardening, so that the amount of metal to be ground from any part is not excessive.

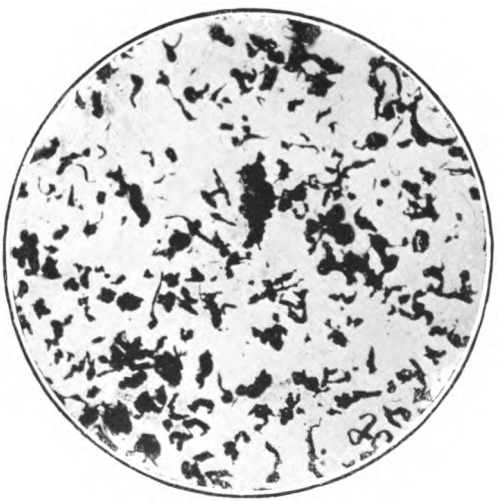

FIG. 36.—Grinding sparks caught on glass plate. x 20.

The soft spots produced by grinding will also etch dark when immersed in the acidified spirit, but they do not etch so readily nor to the same uniform black tint as those due to retarded quenching unless the surface of the steel has been momentarily raised to redness. A hardened steel surface may be momentarily raised to redness by pressing it against

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an emery wheel without any appearance of redness being visible during the operation. Under such circumstances the mass of cold metal cools the hot surface with a rapidity comparable with that of quenching. So that a hard patch could be produced on the surface of unhardened steel or a soft patch on the surface of hardened steel by the same kind of operation. Either case might be an example of retarded hardening, such as arises from imperfect quenching, and the patch would then etch very dark in the acidified spirit, and exhibit also the cellular fringe illustrated by fig. 34.

STREAKY TROOSTITE.

But no serious confusion is likely to arise in the effort to distinguish between very dark etching areas which may be ascribed to the hardening and those ascribable to the grinding operation. At comparatively low magnifications the latter kind exhibit streakiness due to the varying effect of the separate grains in the emery wheel (see fig. 37), whereas the former is an amorphous stain without any distinctive kind of pattern whatever.

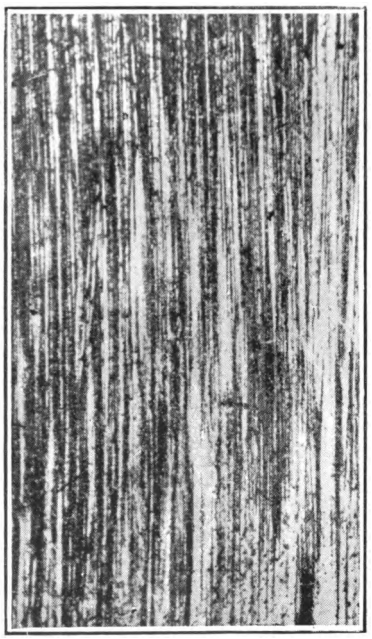

FIG. 37.—Streaky troostite due to grinding. x 25.

The fact that a grinding wheel does remove metal by carving out successive furrows from its surface may be illustrated by carefully grinding the cutting edge of a hardened and tempered tool such as a joiner's firmer chisel. The fash adhering to the cutting edge may be seen to be a fringe of fine flexible steel strips, as in fig. 38, which have been separated from each other at distances corresponding to the coarseness of the emery grain. A perfect fringe can be reproduced on hardened and tempered steel only; on soft steel it becomes shapeless, and on hard steel it breaks away before it can be completely formed.

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CRACKS AND SPLINTERS

The occurrence of soft spots, whether due to imperfect quenching or grinding, may cause cracks and flaking on the face of case-hardened objects. In considering the conditions favourable to actual rupture, it must be remembered that the surface of the hardened object is permanently expanded. But the soft portion is not permanently expanded to the same extent, and must therefore, so long as it remains a continuous part of the surface, be in a state of tension and actually stretched. This softer part is least capable of stretching near its edges, and any disturbance, such as slight rise in temperature or shock, may cause the limit of ductility to be over-stepped. The soft patch being now free to move on its own account contracts on itself, and leaves a distinct break about the outline dividing the harder and softer portions. An instance of this kind occurring on the surface of a case-hardened ball race is shown in fig. 39, which also by the file marks illustrates the relative softness of the splintered portion. When flakes of this kind are removed

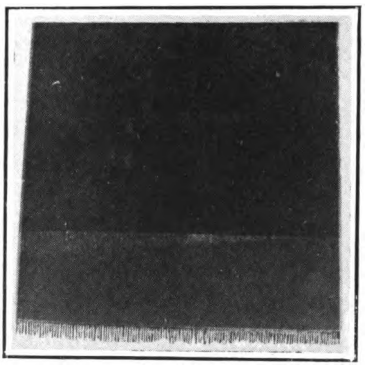

FIG. 38.—Fringe on edge of joiner's chisel.

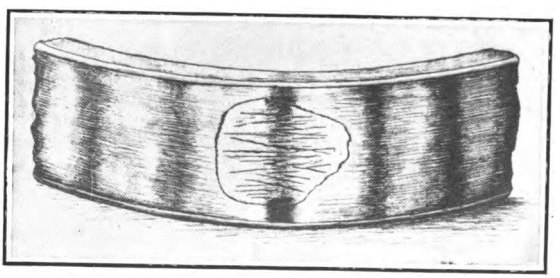

FIG. 39.—Soft splinter on hardened ring.

they are generally found to be thicker in the centre and tapering to a very thin edge; they are also harder on the underside.

Cracks not accompanied by a notable degree of surface

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softening may also be due to grinding. The artisan who aims to produce glass-hard surfaces should not forget that "glass-hardness" and "glass-brittleness" are closely associated properties. It is not surprising that a sharp blow will break a brittle object, because, as is well known, such objects cannot readily change their shape under stress. But the heat of friction due to rash grinding will set up local expansions which the material is too rigid to accommodate, and one or more cracks are inevitable. The steel maker is frequently called upon to replace material in which cracks that he is not at all responsible for have been developed in grinding. Such cracks arise very readily during the grinding of interior surfaces, and also during the grinding of flat surfaces which cannot be effectively water-cooled. Their formation is also greatly aided by the presence of free cementite in the cemented layers. A good example of grinding cracks on the face of a hardened washer is shown in fig. 40. In the first instance the cracks may be almost invisible to the naked eye. They become noticeable on ringing. They may also be made very distinct by soaking the object in a dilute solution of ammonium chloride, and then, after washing and drying, allowing to remain in a dry place for a day or two. The ammonium chloride solution, which penetrates into the cracks, causes the surfaces to rust, and either forces them apart or is itself pressed out of the cracks, and leaves distinct outlines like those seen in fig. 40.

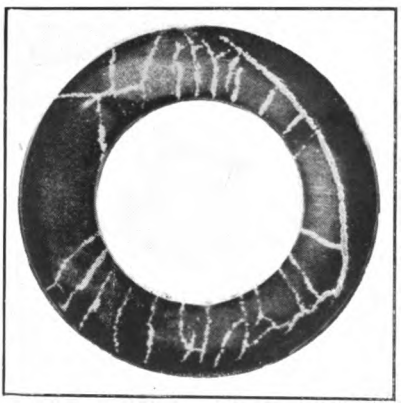

FIG. 40.—Cracks in flat surface of ground washer.

During the grinding of interior surfaces—cam rolls, for example—the cracks due to grinding lie usually at right angles to the axis of the emery wheel, whereas most of the cracks which can be ascribed to defects in the steel lie parallel to the axis of the wheel, *i.e.*, along the direction in which the original bar of steel from which the articles were machined was rolled or forged.

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V.

THE CARBURISING OPERATION.

In order to carry out the carburising operation economically on a large scale, plant of a varied and special kind has from time to time been designed. The arrangement of such plant will vary according to the particular purpose in view, but it does not fall within the scope of this book to discuss either the design or the arrangement of plant, as any such questions must necessarily be decided according to local circumstances. It depends, for example, entirely on circumstances whether the carburising material should be bought or prepared in the factory; and then the manner in which it should be prepared will depend on the material it is thought desirable to use, which varies considerably, and with very good reason, from one factory to another.

Furnaces.

It, therefore, it is said that the cementing surfaces should be fired with either producer or coal gas, it is not to be assumed that coal or coke-fired furnaces are necessarily unfitted for the purpose, or that they are inferior even under certain circumstances. In order to handle large quantities of material cheaply, it is necessary to employ large furnaces, and such furnaces never attain the same temperature throughout even when they are heated by gas. This, however, is not a serious disadvantage, because, if the temperature prevailing in different parts of the furnace is known, use can be made of it by placing those objects in which a deeper casing is required in the hotter parts. The extent to which the temperature varies may be determined either by inserting a thermo-couple, or by focussing an optical pyrometer successively in different parts of the furnace. For determining the maximum temperature attained in inaccessible places—*e.g.*, the inside of a box—some substance having a definite melting point, such as a Sentinel pyrometer, may be used. Variations of temperature in different parts of a furnace also exist according to the manner in which the boxes are placed in it, and unless this matter and other details, such as proportion of gas and air, position of dampers, etc., are taken into account, any predetermined variation of the temperature can hardly be reliable.

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BOXES. Cast iron boxes are cheaper than those made from welded or riveted boiler plate, but they are not so durable, and perhaps not so reliable or economical for regular use. But the possibilities of the cast iron box have been by no means exhausted. During the last few years a large number of observations have been made, notably by Prof. Carpenter, of Manchester, of the behaviour of cast iron during such repeated heatings and coolings as case-hardening boxes are required to undergo, and it appears that ordinary foundry iron is about the worst kind of cast iron that could be used, the reason being that the silicon which is contained in all grey iron gradually oxidises, and in doing so causes the iron to grow in volume, and ultimately crack and crumble. But white irons, *i.e.*, irons comparatively low in silicon, do not exhibit a tendency to grow to the same disagreeable extent, particularly if they contain also a moderate amount of manganese. White iron boxes are, of course, brittle, but if they are properly "let down" after casting they rarely fail on that account. White iron boxes can be used only if the maximum temperature in the cementing furnace is well below 1,100° C., and they cannot easily be straightened when they get out of shape, but they are, nevertheless, a useful alternative to the grey iron box (which is apparently cheap and easily obtainable) and the more expensive mild steel box.

Cored case-hardening boxes are rarely commendable. It looks, on the face of it, as though there would be some advantage, such as more rapid heating, saving in case-hardening powder, and so on, in using cored boxes for cementing rings, etc., but the advantages are illusory. After a short time the boxes lose their shape, the objects are packed or unpacked with difficulty, the lids do not fit well, and quite a wasteful amount of clay is needed to make them reasonably tight; also the boxes crack in the increased number of corners on account of stresses and increase of volume induced by heating and cooling. In all cases where cast iron objects, whether they be cementing boxes, lead pots, or ingot moulds, are repeatedly heated and cooled, any intricacy in design should be suspected, and all sharp angles should be avoided.

Lids for the boxes are more efficient if made to slip inside; they can then be easily luted and made nearly gas-tight. As the pressure of the gases liberated or formed from solid

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carburising material in the heating operation is not without influence on the degree and depth of penetration obtainable, the lid should be luted with a clay mixture that will not crack when dried and heated. Some operators arrange a layer of cast iron borings under the lid in order to lessen the danger of oxidisation if by chance the lid should leak. It is even feasible to use a layer of cast iron borings instead of a lid, as they frit together and make a passable cover; but a properly luted lid is generally more reliable, cheaper, and more convenient.

The boxes used should be as small as is consistent with effective carburisation. The dimensions of boxes are deter-

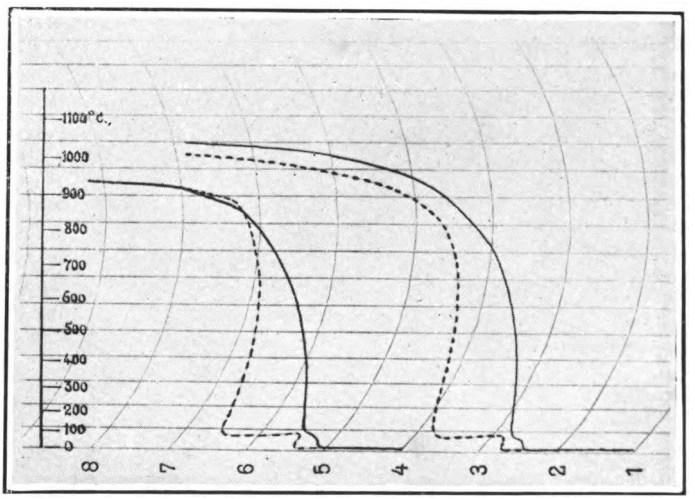

FIG. 41.—Heat conductivity curves of wood charcoal and Caron's mixture.

mined by the size of the object plus a layer of, say, two inches of the carburising mixture. It is better to use a number of smaller boxes than a single large one, not only on account of facility of handling, but also because the results are more uniform. It is an easy matter to heat a furnace to, and maintain it at, some definite temperature, but it is by no means easy to determine the temperature in any particular part of a large box, nor to compute the time which elapses before that part is likely to have attained approximately the furnace temperature.

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CONDUCTIVITY OF MIXTURES.

Case-hardening mixtures vary considerably in respect to their heat conductivity, and irregularity due to uneven packing cannot be entirely left out of account. In order to obtain some concrete idea of the influence which might be exerted by this variation, trial bars extending across the breadth or length of the box, and lying in a central position, may be cemented and afterwards hardened and broken, or used in some other way, to determine the relative amount of penetration. Where recording pyrometers are available it is an easy matter to make a qualitative comparison between one kind of carburising material and another in the following manner:

Two holes are bored through the same side of a carburising box which is, say, five or six inches square; the holes are tapped and provided with pieces of wrought iron gas piping long enough to protrude through the door of a small gas-fired furnace in which the experiment is to be made. One of the tubes is intended to admit a thermo-couple which extends half-way across the box and close up to the side; the second thermo-couple extends an equal depth and lies with its fused junction in the centre of the box. The box is then filled with the trial mixture and packed by jolting. The open ends of the tubes are packed with asbestos and smeared with fireclay in order to make a gas-tight joint. The furnace is then heated at a uniform rate by turning on at once as much gas as is necessary to raise the temperature of the furnace to the desired degree. The results obtained will be similar to those reproduced in fig. 41, which refers to wood charcoal (the inner pair of curves), and the mixture of wood charcoal and barium carbonate which is sold as "Hardenite," and sometimes spoken of as Caron's mixture (the outer pair of curves).

The broken line curves are records made by the couple in the centre of the box; the full line curves were made by the couple lying close to the side of the box. In each case the broken line curves show a long halt at 100° C. extending over the period during which the two or three per cent. of moisture in the mixture was being volatilised. It should be especially noticed that whereas the recorded curves for wood charcoal become ultimately coincident, those for Caron's mixture do not, *i.e.*, in the latter case the interior of the box never reaches the actual furnace temperature. The same statement applies whether the charcoal and Caron's mixture is freshly prepared or has been previously used.

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The results of a number of observations along similar lines have been recorded by Nead and Bourg (*Iron Age*, 1912, page 904). They heated a lead bath to constant temperature, and recorded the time required for a thermo-couple placed in the centre of an immersed pot and surrounded with a carburising material to reach the same definite temperature. They examined—

Materials.		Weight per cubic foot.	Time to reach 1,200° F.
		lbs.	mins.
Ordinary grade raw bone	new	52	145
,, ,, ,, ...	old	—	99
Coked mixture of coal, soda ash, and limestone	new	28	52
,, ,, ,, ,, ,,	old	28	34
Wood-charcoal-barium carbonate ..	new	35	110
,, ,, ,, ,, ..	old	—	96
Bone-charcoal-barium carbonate ..	new	45	112
Mixture of wood and bone charcoal		—	150
Charred bone with 25 per cent. hydrocarbon oil		—	143
Special charcoal and calcium saccharate	new	51	114
,, ,, ,, ,, ,,	old	—	76

SOFT PLACES.

If it is intended that certain parts of a cemented object should remain soft after quenching, then those parts must be protected not only from actual contact with the solid carburising agent, but also from contact with the evolved gases which are diffused throughout every permeable part of the interior of the box. For filling up interiors, tapped holes, and the like, a siliceous clay mixture may be satisfactorily used. If the clay is too " fatty " and shrinks badly on heating, it may be mixed with a burnt fireclay, crushed firebrick, granular plumbago, coke dust, or some non-shrinkable substance in such amounts that the plasticity of the mass is not entirely lost; and to increase its fusibility the dry mixture may be moistened with sodium silicate (water glass). Brick clay which will just frit at the case-hardening temperature is generally more suitable than the more refractory clays.

But neither clay nor asbestos wrappings, nor the use of any other adhesive substance, are really satisfactory means of protecting outer surfaces. One of the most satisfactory of such substances is a mixture of sodium silicate and very finely ground sand, which is put on with a brush to a thick-

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ness of about 1 mm., or rather less, and allowed to dry in a warm place before packing in the cementing box. Fig. 42 is a polished and etched section of a round bar which has been kept soft midway in its length by the use of this protective paint. Though an electro-deposited plating of copper or nickel has been suggested, and is reported to be a satisfactory means of preventing carburisation, it is not generally adopted by industrial concerns. Nor has the much simpler plan of rubbing an acidified solution of copper sulphate (or chloride) over the part it is desired to keep soft met with great success. The method of producing the nickel deposit is probably too expensive and cumbersome, and the copper deposit is not quite reliable unless it is above a certain thickness and as dense as it can be made by electro deposition only. The most widely-used reliable plan with straight articles such as piston pins is to leave the part which has ultimately to remain soft greater than the required diameter and turn off the surplus material between the casing operation and the first quenching operation. A satisfactory result may also be obtained by shrinking a thin iron sleeve on to any particular part of a straight round object, and removing it by a tap with a hammer after the object has been cased and quenched.

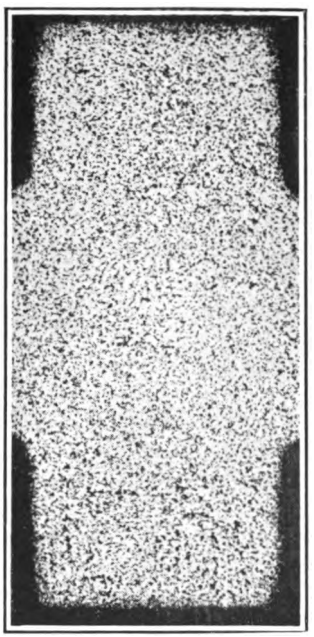

FIG. 42.—Middle part of bar shielded from carburising effect. x 5.

CARBURISATION.

And now that the articles have been packed in a box of the proper dimensions, with a suitable kind of carburising material, free from moisture or other readily volatile impurity; and every provision has been made for securing soft places where they are required as well as for exposing the boxes to the desired temperature, we may consider by what means the carbon enters into combination with the

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iron. It is possible to cement the surface of hot iron by bringing pure carbon into contact with it so that by a direct reaction between the carbon and the iron the two will combine. But a reaction of this direct kind does not take place to an appreciable extent at such temperatures as are usually employed in cementing furnaces. In all forms of industrial case-hardening the actual carburisation is due to the hot gases which are either liberated by the case-hardening compound or formed by a reaction between the occluded air and the powder. This statement can be easily confirmed.

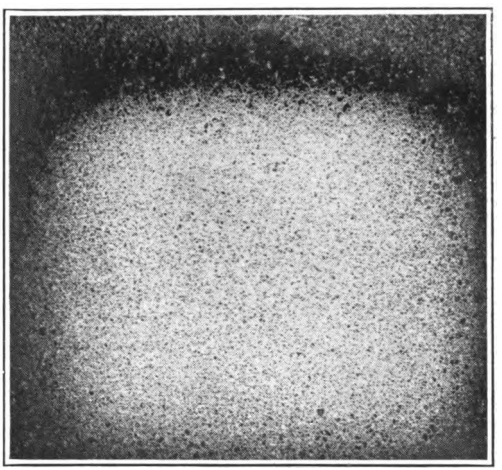

FIG. 43.—Section of bar in contact on one face only with case-hardening powder. x 5.

If a piece of a square bar of mild steel be packed in sand almost to its upper surface, and, after covering the sand with asbestos paper, the box be then filled with some solid case-hardening mixture—say charcoal and barium carbonate —and fired, it will be found that carburisation has taken place not only on the upper face of the bar, but also to a considerable degree on every other face of it. Fig. 43 represents such a bar, which, after treatment, was polished and etched on a transverse section. There are numerous opportunities in workshop practice of making this observation, the penetration in some cases being almost as great into those surfaces out of contact as into those surfaces in contact with the carburising mixture.

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ACTION OF GASES.

A simple, if not very accurate, means of picturing the process whereby those portions of a bar not in direct contact with the powder become cased is to assume that the carbon monoxide formed in the box becomes decomposed as follows:

$$2CO + 3Fe = Fe_3C + CO_2,$$

the CO_2 in turn being readily reduced again by the excess of charcoal to CO. This reaction by no means explains everything, nor, for that matter, do the apparently learned explanations which rely on certain gymnastic transformations of nitrogen to produce complex cyanides. That a cyanide bath at a suitable temperature will cement the surface of mild steel is, of course, a well-known fact, but most case-hardeners are also aware that mild steel can be cemented by gases, and, amongst others, by carbon monoxide, which contain no nitrogen compounds. It seems, therefore, advisable to accept the simpler explanation, and, whilst preserving an open mind, to welcome assaults on our ignorance. It may, at any rate, be concluded that the active case-hardening reagent is a gas, or a mixture of gases, liberated from the hot powder, and not the solid powder itself.

Whether the action of the carburising gases is confined to the surface formation of iron carbide (Fe_3C), which diffuses as a solid into the iron, or whether the gases themselves penetrate and are decomposed in the metal, is a question not yet answered in a manner which meets with unanimous approval. It is known that solid substances do diffuse into each other, and it has been demonstrated experimentally that a core of hard steel will diffuse into a sleeve of soft steel pressed into intimate contact with it when the two are heated above certain minimum temperatures. We are also aware, from a previous consideration of the phenomena illustrated by figs. 6 to 10, that carbide (pearlite) areas will diffuse into carbonless areas. But all these diffusions of the solid constituents of steel amongst themselves act through very small distances, which are practically negligible compared with such depths of penetration—up to 20 mm.—as are regularly attained in manufacturing operations.

DECARBURISATION BY GASES.

Although it may be difficult to present direct evidence, there is a good deal of indirect evidence in favour of the view which limits the inter-diffusion of solid constituents in steel to fields of microscopic dimensions, and ascribes the carburising effect to the penetration of the carburising gases into the metal. This view is most readily illustrated, but not

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proved, of course, by observing the effects of the decarburising process. A bar of steel which has a decarburised surface may be regarded as a very favourable specimen in which to witness solid diffusion over appreciable distances, if such occur, because the continuity between the carburised and carbonless portions is perfect. But if such a bar is heated to temperatures usually employed in case-hardening operations and quenched, the thickness of the carbonless envelope remains for all practical purposes as great as before. If solid diffusion could take place across the carbonless envelope, then it might be reasonably expected that carbide from the inner core would diffuse gradually outward and exhibit a

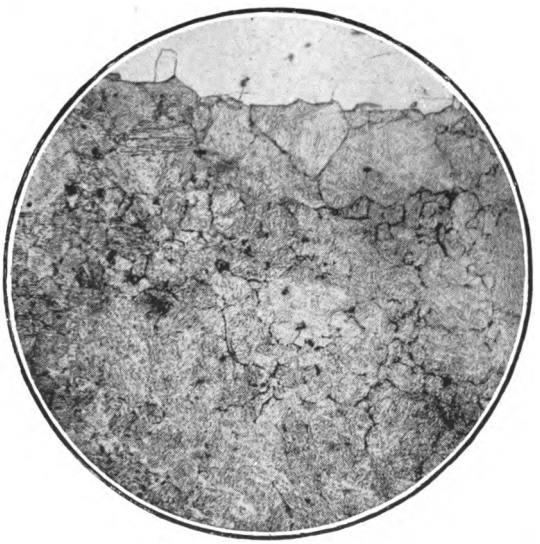

FIG. 44.—Quenched bar with sharply defined carbonless envelope. x 100.

measurable amount of carbon on the extreme edges even. It is found, on the contrary, that the division between the carburised and carbonless parts is quite sharp, as illustrated by fig. 44; and it may be taken at least as highly probable that both carburisation—as in case-hardening—and decarburisation are brought about by penetration into the metal of the reacting gases. There is, of course, nothing novel in the idea that gases penetrate into solid metal. If a piece of steel is heated in vacuo, gases are liberated from it. When grey cast iron grows and spalls or cracks, it is

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because the silicon it contains becomes oxidised by the permeating gases; and when steel becomes brittle on pickling, or blisters on the surface, the reason again is ascribed to the hydrogen gas liberated in the operation being absorbed by the metal.

SLOW COOLING.

Free cementite, which causes so much trouble in the hardened case by way of cracking and splintering, may occur also in the core of case-hardened objects which have been allowed to cool very slowly in the cementing boxes. All case-hardening powders are comparatively bad conductors of heat, and the contents of large boxes will remain at red heat

FIG. 45.—Thickening of carbide plates in pearlite areas due to slow cooling. x 200.

for many hours if allowed to cool undisturbed after withdrawing from the furnace: this is an additional reason why needlessly large boxes should not be used. But if the steel exposed to these unfavourable conditions happens to contain only a very small amount of manganese, then, during the very gradual transformation from solid solution, the pearlite does not break up into alternating laminæ disposed uniformly after the usual manner of mild steels, but deposits its carbide in a more massive form which responds to etching reagents like free cementite. Such segregations of free cementite in mild steels vary in degree from the thickening of carbide

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plates in pearlite areas, as seen in fig. 45, to the formation of membranes which partly or completely separate one crystal from another; and the resulting material in the latter case is as brittle under shock as though it were razor steel.

The photograph reproduced in fig. 46 (section etched with sodium picrate) illustrates the cell-like form of free cementite which confers on very mild steels (carbon .10 to .30) an extraordinary degree of brittleness. The author has observed this defect also in lifting tackle, such as crane hooks, which had been forged from mild steel and cooled very slowly in the annealing process. The defect can be overcome by reheating

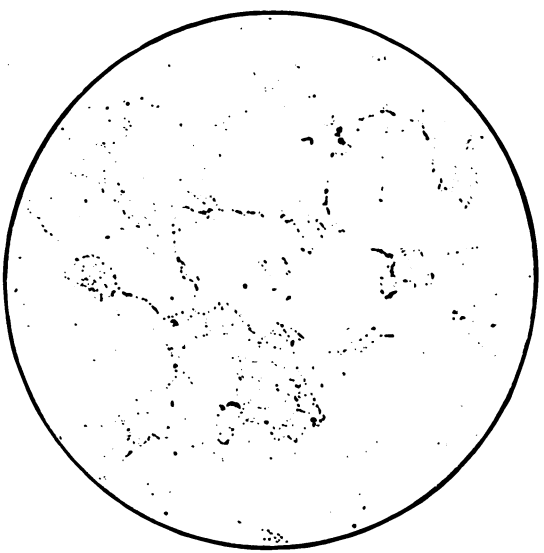

FIG. 46.—Cementite envelopes in slowly-cooled mild steel. x 100.

the steel to a temperature at which the carbide becomes again completely and uniformly diffused into the surrounding iron, *i.e.*, generally by heating to 950° C. and avoiding a subsequent slow cooling. By way of example, the following impact figures relating to a crane hook which contained C .09 and Mn .30 per cent. may be given:

After slow cooling in annealing furnace, 4 ft. lbs.

After reheating to 950° C. and cooling quickly, 86 ft. lbs.

The microstructure of the original material was like fig. 46, but the microstructure after treatment was in all respects like that of a normal steel, *e.g.*, fig. 50. The ordinary

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tensile test results did not give the slightest indication of the extreme brittleness of the material. They were:

Yield point	.. ..	14.0 tons per sq. in.
Maximum stress	..	25.5 ,, ,,
Elongation	.. ..	40 per cent. on 2in. ×.564in.
Reduction of area	..	69.8 per cent.

DEPTH OF PENETRATION.

The depth to which the cementing effect extends can be determined roughly by examining the fracture of a hardened bar. The distinction between the casing and the core varies according to the size of the bar and the treatment before quenching. In small bars the casing is relatively not so deep as it appears to be, and in bars quenched direct from the cementing furnace the core and casing appear to run into one another because both of them have a coarsely crystalline structure. When the core is refined by an intermediate treatment between 900-950° C., followed by rapid cooling in air, or oil, or water, and the piece is subsequently reheated to 760°-780° C. and finally quenched, then the core and casing stand out with greater distinctness. If finally the quenching from 760-780° C. is done in oil instead of water, the distinction is still more marked, and especially so if the steel happens to contain a large amount of manganese. The reasons for these differences in appearance are fairly obvious, and the degree of distinctness attainable in small bars by quenching finally in oil and water is illustrated by fig. 20.

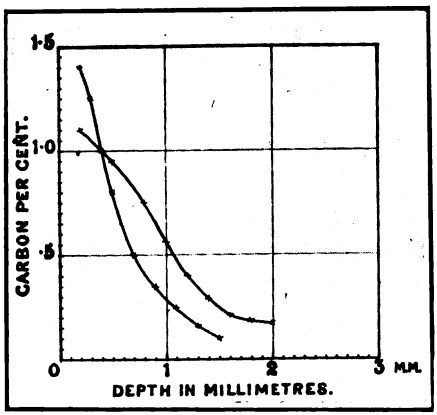

FIG. 47.—Degree and depth of carburisation as determined by chemical analysis.

PENETRATION CURVES.

None of the above methods, however, yield accurate information either as to the degree of penetration or the degree of carburisation. For this purpose two methods are in use. The first and oldest is to turn successive layers off the round bar one or two-tenths of a millimetre thick, and, after determining the amount of carbon in the separate portions by analysis, to plot the results in the form of a

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curve, as in fig. 47. Such curves indicate not only the depth of penetration, but also by their steepness the manner in which the carbon decreases. This method, though sometimes indispensable, is too cumbersome for general use.

PHOTO-RECORDS OF PENETRATION.

The second method consists in examining a polished and etched section under the microscope, or, in some cases, with sufficient exactness by means of a good hand lens. When intended for examination in this way, the bar should be allowed to cool in the case-hardening box so as to retain the coarse structure due to the high cementing heat, and the carburised layer in an undiffused condition owing to the

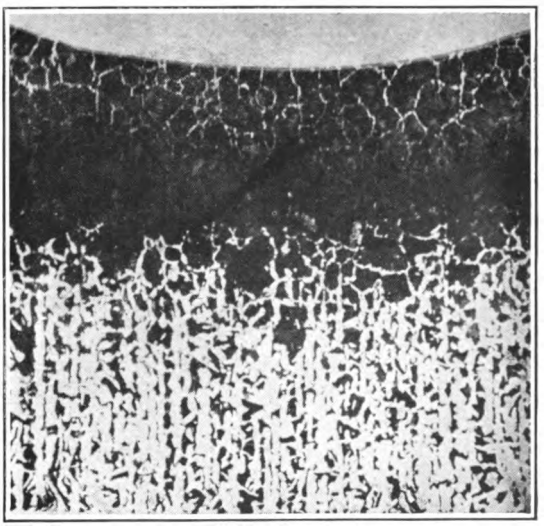

FIG. 48.—Degree and depth of carburisation as seen on polished and etched section. x 25.

slower cooling. Fig. 48 represents a specimen prepared in this manner, from which one can see clearly a complete record of the information sought. A further advantage of making this observation on the coarsely crystalline material is that an intelligible photograph can be produced at low magnification (generally twenty-five diameters) embracing the entire field of interest.

It is also possible by the optical method to see the extreme surface of the specimen, which occasionally contains an undesirable amount of cementite, the extent of which would not be revealed by taking successive cuts one or two-

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tenths of a millimetre deep. In order that the extreme edge may be sharply defined and not rounded in the polishing operation, it is desirable to place the specimen inside a short brass ring—a piece of brass tubing—and cast white metal around and underneath it. The distinction between the two metals after grinding is sharply defined, and the edge of the steel is brought into sharper focus at the same time as the other part of the surface. The author is indebted to his

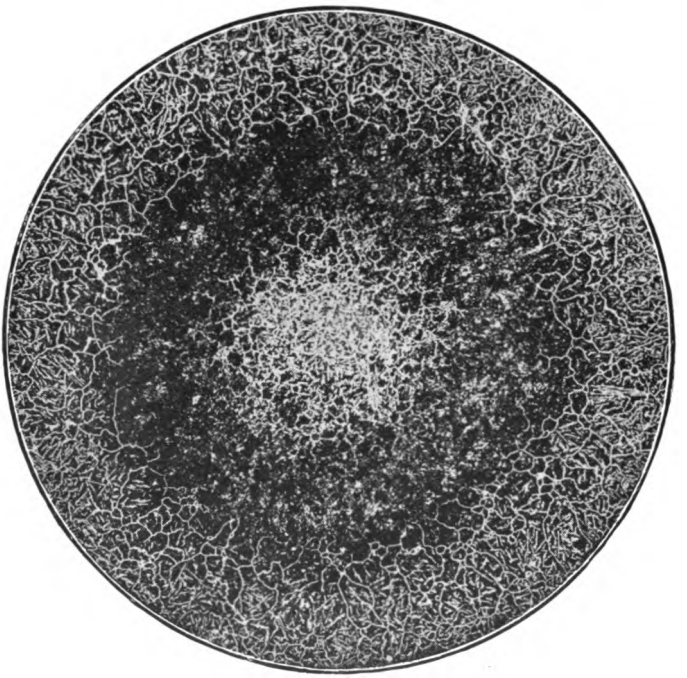

FIG. 49.—Entire cross section of case-hardened bar.

friend Dr. Schäfer for the photograph reproduced in fig. 49, which represents the entire cross section of a small bar, deeply carburised, in a clear and most instructive manner.

In order to verify the statement that such and such a case-hardening medium will give certain penetrations after so many hours at a prescribed temperature, it is desirable to specify the size of the trial bar used, though, within certain limits, the size of trial bar is not of great importance. Still, in the practice of any particular works some bar of definite size should be adhered to, and the fact that all kinds of steels

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are not cemented to an equal degree under like circumstances ought not to be overlooked. The most reliable practice, though by no means the most convenient, is to cement flat bars, in which case the ends and sides must be milled or filed away before successive millings are removed from the surface for analysis. In other respects the square or oblong is the better form of bar to use, because the sharp edges are a very sensitive indication of any danger arising from the formation of free cementite. This, as is well known, leads to the objectionable feature spoken of as "freckled corners," which can be found in case-hardened gear wheels, ball races, and similar objects having sharp edges or edges of small radii which have been cemented under conditions that would not produce free cementite in a trial bar of round section.

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VI.

CASE-HARDENING STEELS.

THE selection of steels for the manufacture of case-hardened objects is a matter that might be advantageously discussed with the steel maker. The special information on both sides, if wisely used at the beginning, will avoid later troubles for which nobody appears to be responsible. Case-hardening steel is no longer the cinderella of the steel trade, and the steel maker is generally willing to improve his acquaintance with the more exacting requirements of the builder of machines and automobiles.

MACHINED SURFACES.

Wrought iron in the case-hardened state would be more extensively used if it could be finished as smoothly and machined as sweetly as mild steel. Its extreme toughness and the fibrous nature of a fractured surface are to many minds ideal qualities; but its use frequently involves grinding, or finishing in some other way, after it has been machined into the required shape. Some mild steels are not free from the same defect which becomes intolerable when small pins, bushes, screws, complex driving gears, and other objects that must be given their finished shape and dimensions on a cutting machine are being manufactured.

It is almost an axiom amongst machinists that a piece of steel which has been hardened and then reheated to low redness and quenched in water will cut tougher, but finish smoother, than the same steel in any other condition. In certain factories it is considered that the quenching and reheating of the steel bars to be used for screw-making, etc., are decidedly worth while merely on account of the superior finish thus obtained, leaving entirely out of account the improved strength and toughness of the articles.

This observation may be taken as an indication of the direction in which to look for an explanation when steels identical in composition and possibly from the same delivery are found to be erratic in respect to machinability. If soft iron pulls and tears under the tool, then soft iron as such must be eliminated as far as possible. The hardening operation, according to the exposition on page 9, produces an inter-diffusion of the carbides through all the surrounding soft

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iron parts, and the reheating does not seriously interfere with the attained structural arrangement; it is for this reason that all steels which contain free ferrite—from, say, .70 per cent. carbon downwards—are improved in their machining (finishing) properties by hardening and then reheating to a temperature below the hardenable range, which leaves them almost as soft as they were before. The final effect of this treatment on the maximum tensile stress may be negligible, but the yield point of the material is raised and its toughness is greatly increased; the immediate object, *i.e.*, good finishing properties, is therefore attained in association with properties which increase the reliability of the material and its durability under all forms of stress, wear, and erosion.

But steel which has been hardened and reheated in order to improve its machining qualities loses all the associated advantages in the subsequent cementing operation. The case-hardener, therefore, requires that the steel should be delivered into his warehouse in a fit state for machining with the required finish, as he, very naturally, hesitates to incur the expense of an additional operation for a temporary benefit only if the same can be avoided. And the steel maker, knowing likewise that his material will be necessarily overheated in the cementing operation, does not willingly undertake the trouble and expense involved in hardening and quenching such bars as are machined directly into the required forms.

CAUSE OF ROUGH FINISH.

The reason certain bars of mild steel machine in a manner akin to wrought iron is because they consist largely of pure iron (ferrite). But the trouble arises not so much from the indispensable amount of pure iron they contain as from the manner in which the constituents, *i.e.*, the pearlite and ferrite patches, are distributed and their relative dimensions. A very hard substance such as glass may be so thin that it can be cut with a pair of scissors just as the very hard carbide of iron existing in the pearlite areas of annealed chisel steel is cut; and in the same way a soft and tough material which is alternated or well mixed in a fine state of division with harder substances can be cut without dragging or smearing under the tool. It might therefore be expected that any operation which promoted the uniform distribution of pearlite and ferrite areas of small dimensions throughout the bar of mild steel would improve the finish with which it could be

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machined, and so it does. Hardening and reheating may be regarded from the present point of view as an extreme instance of uniform distribution of the harder and softer constituents brought about by the agency of heat treatment alone. It is well known, however, that an effect in the same direction can be attained by mechanical work, and it will be found that soft steel which has left the hammer or the rolls at a bright red heat machines less satisfactorily than the same kind of material which has been finished at low redness.

The steel maker who is not directly concerned with the machining of the material, and knows that in any case it will

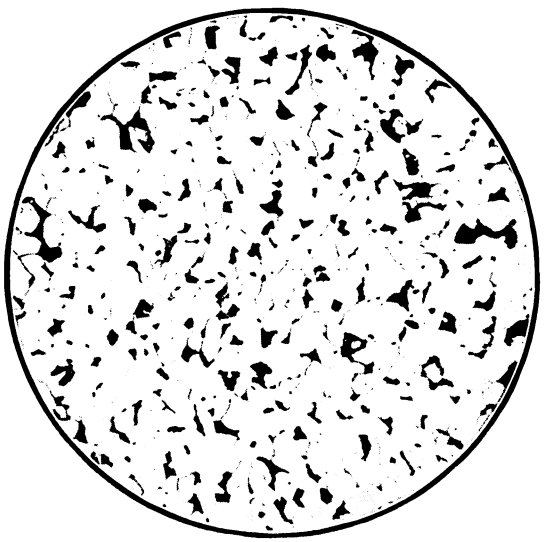

FIG. 50.—Steel which machines well. x 100.

be subsequently overheated, is apt to take advantage of the fact that very mild steel, like wrought iron, will "stand fire" and roll the easier if made very hot. The consequence is that bars, instead of having the fine uniform structure of fig. 50, which is associated with good machining properties, have frequently the structure of fig. 51, which is associated with indifferent machining properties because the ferrite areas are large enough to pull up into visible forms of roughness. If objects have to be ground on the surface after cementing and hardening, a rough finish is still not free from objection, as the torn surface in the hardened condition is

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more favourable to the starting of surface cracks and splintering. The difficulty of commending this conclusion to the mind of some steel makers might be considerable, but it is none the less an example of the fact that levity in the handling of steel is rarely quite as insignificant in its results as its perpetrator imagines.

Although the above remarks refer especially to bar steel, they are equally applicable to drop forgings, which might with advantage undergo the hardening and reheating treatment in order to break down coarse structures as well as to facilitate machining. The ferrite bands illustrated by fig. 26, if of comparatively great width, will also pull on machining,

FIG. 51.—Similar steel to fig. 50, which machines badly. x 100.

and particularly if the cutting tool happens to have a negative rake. Other things being equal, a steel will machine with a smoother surface as the amount of carbon in it increases, though this is rarely a justifiable reason for increasing the carbon. Manganese, tungsten, and chromium act in the same direction, because they decrease the size of the crystalline grains and retard the segregation of ferrite into large patches. Silicon and aluminium might be expected to exert a contrary influence, but neither of these elements is a favourable ingredient in case-hardening steels, and recorded experience with them is not generally available.

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CARBON STEELS.

Dead-mild steels containing about .10 per cent. of carbon and minimal amounts of silicon and manganese are greatly in vogue for case-hardening purposes, and are no doubt indispensable for the production of very small objects which require to be both cemented and hardened without becoming brittle: the small bushes and pins which go to the making of chain drives belong to this category. The nearer the steel used for such purposes approximates to the composition and properties of wrought-iron without sharing in the objectionable presence of slag streaks and seams the better. But it does not follow that larger objects in which the soft core could be retained without difficulty should also be made from similar material. Both occluded slag and blowholes are likely to be more prevalent in what is appropriately called "ingot iron" than in material containing greater amounts of carbon, silicon, and manganese. The occurrence also of slag membranes is more frequent in steels of the former kind, and, though these are negligible so far as the core is concerned, they exist also in the cemented case, and increase its brittleness just as seams and slag streaks break up its continuity.

Whenever, therefore, the core is desired to withstand a crushing load, or whenever a portion of its toughness can be sacrificed, it is desirable for the sake of an improved case to use steel containing .15 per cent. carbon or more, together with upwards of .30 per cent. manganese. The core of such a steel can be made very tough by double quenching, or perhaps by final oil quenching, according to circumstances, with minimum brittleness and the required degree of hardness.

MANGANESE STEELS.

Guillet, of the Dion Bouton factory in Paris, who has devoted a great deal of time to the study of case-hardening problems, fixes the maximum amount of manganese which should be present in case-hardening steel at .40 per cent. Though generally adhered to for steels used in the manufacture of small articles, this recommendation, in England at least, is ignored so far as the larger articles are concerned. Apart from any advantage it may be to the steel-maker, the presence of manganese is favourable to the production of strong cores which support the casing under heavy compression loads. The view that a core cannot be too soft and flexible appears to be erroneous, because the core and casing must deflect simultaneously, if at all, and any serious

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deflection in the casing produces a crack and spoils the article. This fact would appeal more strongly to the minds of case-hardeners if the machines they employ for fracturing hardened test-pieces were provided with means whereby the effort required to produce fracture could be read off in concrete figures.

Manganese is perhaps the most active of all elements known to the steelmaker in its effects on the stability of pearlite areas in the inter-diffused state induced by heating to the hardening temperature; or, as expressed by the hardener, it causes the quenching effect to strike deeper. This is clearly an advantage which can be modified within fairly wide limits to suit particular circumstances: and one of the most useful of these modifications is that the final hardening may be done in oil instead of in water. It is, therefore, possible to harden bars as small as ½in. diameter so as to retain in the first quenching a completely diffused core, and in the second (oil) quenching to produce a perfectly hard case and a core which is at the same time stronger and equally as tough as it could otherwise be made if a lesser amount of manganese were present. Fig. 20 represents the fractured surface of such a bar.

Manganese also improves the wearing quality of steel. Of two normal steels which are equally hard—the hardness being measured by the Brinell machine—that steel containing the greater amount of manganese and the lesser amount of carbon will best resist wear. This view is supported by all tests on wear-measuring machines, and it has been confirmed incidentally by the machines which are now in regular use for testing files. A file will wear out much quicker on a piece of tyre steel containing, say, .65 per cent. carbon and .80 per cent. manganese than it will on a piece of equally "hard" crucible steel which contains, say, one per cent. carbon and .25 per cent. manganese. There are no data to show explicitly how two such steels would behave in the quenched state, but there is a general impression, based on experience, that file hardness is not always a true criterion of resistance to wear. For these, amongst other reasons, the use of case-hardening steels containing up to nearly one per cent. of manganese may serve a useful purpose.

CHROMIUM STEELS.

Chromium, up to one or one and a half per cent., may also be present in low carbon steels which are required after casing to possess an exceedingly hard wear-resisting surface.

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The effect of chromium in this respect is very similar to the effect of manganese, but the hardened case is less apt to splinter. On the other hand, chromium steels are readily overheated, and quickly show the effects of overheating in the fracture. This, however, is no serious disadvantage if a refining treatment is interposed between the high cementation heat and the final quenching, as the steel responds very readily to refining operations. The core of case-hardening chromium steel can be made very tough, so that it breaks with a silky grey fracture and a very smooth-grained hard casing. In this respect it is surpassed only by tungsten steel, which is necessarily expensive and not in commercial use as case-hardening steel.

NICKEL STEELS.

Both manganese and chromium are favourable to rapid cementation, and both elements increase the hardness of the carburised surface. Nickel, on the other hand, retards the cementing operation, and does not increase the file hardness of the quenched bars ; in fact, it decreases the hardness to a noticeable extent when the nickel present amounts to six or seven per cent.

The object of nickel in case-hardening steels is to improve its toughness, and this it may do to such an extent that a fibrous core may be obtained even when the intermediate refining treatment is omitted. This in itself is a great advantage when large quantities of long and comparatively thin articles are in question which may become either decarburised or warped during the high temperature quenching. Nickel hardens steel very appreciably in the presence of carbon, and the amount of carbon in the steel, if a soft core is required, should, therefore, not exceed .20 per cent. if associated with two or three per cent. of nickel, or .10 to .15 per cent. if associated with three to five per cent. of nickel.

Some years ago a patent was taken out for the treatment of low carbon steel containing about seven per cent. of nickel which in its normal state was soft and readily machinable. On cementing until the casing contained .9 per cent. carbon such a steel attained a surface hardness when cooled in the air, and it was thus intended to avoid the trouble and distortion which arise from water quenching. These important advantages are, however, lessened by the fact that the surface of the air-hardened steel is less hard than that of water or oil quenched steel. Steels richer in nickel—say between

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eight and fifteen per cent.—are hard and brittle in their normal state and unsuitable for case-hardening purposes. Those steels containing still higher amounts of nickel—say twenty to thirty per cent.—are also unsuitable, as they cannot be hardened by any form of quenching, and are, moreover, very difficult to machine.

The observed variation in the mechanical properties of a series of nickel steels which contained, on the one hand, gradually increasing amounts of nickel, and, on the other, gradually increasing amounts of carbon, has been very aptly illustrated by Guillet in diagrammatic form (see fig. 52).

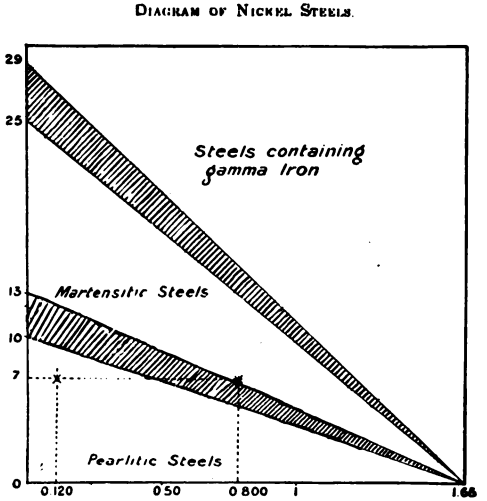

Fig. 52.—Guillet's diagram of nickel steels.

The ordinates correspond to percentages of nickel and percentages of carbon alloyed simultaneously with pure iron. The diagram divides nickel-iron alloys into three groups: the pearlite group, which have the properties of ordinary steel, and can be machined in their normal condition; the martensite group, which have marked air-hardening properties, and are correspondingly brittle and difficult to machine; and the austenite or gamma iron group, which are less hard and extremely tough. The shaded parts of the diagram represent conditions between one group and the other.

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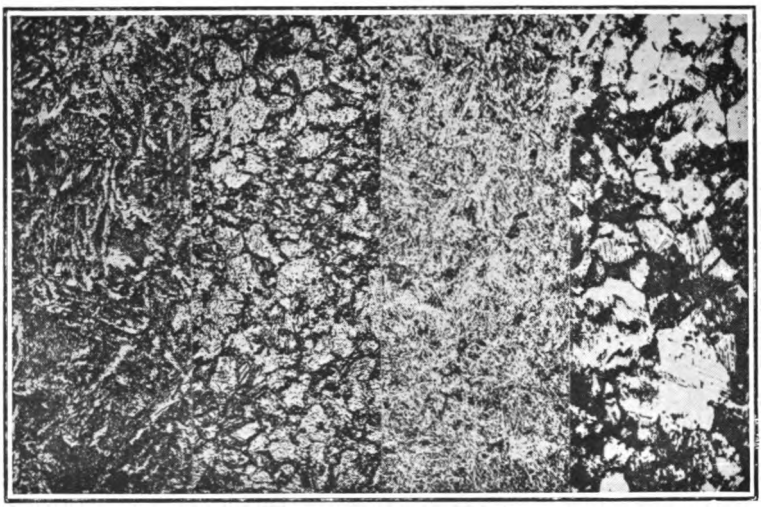
It is not difficult on cementing a piece of steel containing, say, six per cent. nickel to observe after air-cooling all conditions of the material represented in fig. 52. There is, first, the pearlite core; then, as the amount of carbon increases, the structure changes to an intermixture of pear ite, troostite, and martensite, corresponding to the lower hatched part of fig. 52; then nearer the surface the structure becomes entirely martensitic; and finally, on the outer surfaces, the austenite structure appears. These respective structures are typified in fig. 53 as follows:



A B C D

FIG. 53.
Varying structures in cemented bar of six per cent. nickel steel.

A. Pearlite core.
B. Mixture of troostite and martensite.
C. Martensitic structure.
D. Austenitic structure.

If a similar piece of case-hardened nickel steel were cooled *very* slowly the polished and etched section would exhibit structures very much like ordinary carbon steel, *i.e.*, they would consist of ferrite, pearlite, and free cementite in due proportion.

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The diagram, fig. 52, clearly illustrates the fact that the constitution and mechanical properties of nickel-iron-carbon alloys depend on the sum of the nickel and carbon which they contain, and by means of the dotted line it represents the changed condition due to cementation, which enables a mild steel containing about seven per cent. of nickel to attain a hard surface by air quenching only.

NICKEL-CHROME STEELS.

A diagram similar to fig. 52 might also be constructed to illustrate the varying mechanical properties of manganese-iron-carbon alloys or chromium-iron-carbon alloys. It follows, therefore, that the influence of manganese and chromium, if they are present in nickel steels, must be added to the estimated effect produced by nickel and carbon. The exact manner, therefore, in which a steel containing nickel, chromium, and manganese will behave under different conditions of heating and cooling cannot be easily predicted. Variations apparently slight and insignificant will produce widely different results. This accounts for the prevailing impression that chromium-nickel steel is erratic in its behaviour, and can sometimes be machined easily and sometimes not at all. These properties would appear to be especially objectionable in case-hardening steels, and, indeed, it is a matter of surprise that these steels have been so often commended without any reference being made to their natural limitations.

When the amount of chromium in nickel steels does not exceed a few tenths per cent. and the amount of manganese is also low, the steel may be usefully applied to the manufacture of large objects which are intended to be finally quenched in oil. But a steel containing from two to four per cent. of nickel with half that amount of chromium and the usual amount of manganese (.4 to .6 per cent.) would not possess a tough fibrous core if quenched in oil or even if cooled in air. Such material would answer admirably for machine spindles and for similar purposes where great rigidity and a very hard wearing surface is required.

Nickel-chrome steels serve the most useful purpose in the automobile and general engineering trades when they possess air-hardening properties to such a degree that gears and other articles of complex shapes which have to withstand great pressure and hard wear can be made from them, and the distortion due to the usual methods of quenching case-hardened objects may thus be avoided. Their surface hard-

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ness, after air cooling, may be increased by cementation, and such surfaces wear exceedingly well, but are not less brittle than the surfaces of ordinary cemented steel after water quenching. In the uncemented state the surfaces do not become file hard on air cooling, but they resist compression and rubbing wear very well, and combine great tensile strength with a certain degree of flexibility. They may also be tempered after air-hardening up to 300° C. and still retain great hardness and toughness combined. The following figures indicate the range of mechanical properties which may be secured by heat treatment from an air-hardening nickel-chrome steel of the kind suitable for the manufacture of gears.

Heat Treatment after Air-hardening from 820° C.	Tons per sq. in.		2 × .564in.		Brinell Hardness No.
	Y.P.	M.S.	E.	R.A.	
Not tempered	—	129.0	10.0	33.0	512
Tempered at 300° C. ..	102.0	110.0	12.0	44.0	418
,, ,, 400° C. ..	87.0	95.0	13.0	47.0	375
,, ,, 500° C. ..	79.0	81.0	15.0	50.0	340
,, ,, 600° C. ..	59.0	65.0	22.0	60.0	286
,, ,, 650° C. ..	52.0	60.0	25.0	64.0	255
Cooled slowly from 750° C.	26.0	44.0	30.0	66.0	170

Y.P. = Yield point. E. = Elongation per cent.
M.S. = Maximum stress. R.A. = Reduction of area per cent.

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VII.

CARBURISING REAGENTS.

THE most helpful of all generalisations in metallurgy is the one based on observations made with the pyrometer, and confirmed by the microscope, known as the equilibrium diagram. A full description of such diagrams may be read in any modern book* on metallurgy, but as much of the iron-carbon (steel) diagram as is especially useful to the case-hardener may be explained in a few paragraphs.

EQUILIBRIUM DIAGRAM.

From the observations described on page 9 we know already that at a temperature of about 740° C. the pearlite areas in mild steel undergo a transformation which enables them to be hardened by sudden quenching. The same kind of transformation takes place in the pearlite areas of all ordinary steel, whatever amount of carbon it contains, at about the same temperature. This fact may be represented diagrammatically if we draw a horizontal line through F (fig. 54) which corresponds to 740° C., and arrange two rectangular lines representing temperatures and the amount of carbon present respectively in a series of steels. Any steel, therefore, whose temperature has been raised above a horizontal line through F may be hardened, so far as its pearlite areas are concerned, by sudden quenching. But we have learnt also (page 11) that the pearlite areas, having been transformed at about 740° C., begin as the temperature rises higher to inter-diffuse, in mild steel, with the adjacent ferrite areas. At a higher temperature, say 780° C., this inter-diffusion has progressed to a certain extent, and can proceed no further no matter how long that temperature is maintained. But as the temperature rises the inter-diffused areas extend, and finally no more free ferrite is left. This particular temperature, the lowest at which it is possible to bring about complete inter-diffusion, is important, because it is also the lowest temperature at which coarse crystalline structures can be broken down and replaced by finer ones; and it is possible by a scheme of experimental observations such as is indicated by fig. 4 to fix this minimum temperature

* Desch: "Metallography" (Longmans). Gulliver: "Metallic Alloys" (Griffin).

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with considerable accuracy, say, at C for a steel containing .15 per cent. carbon. In the same way we can fix point D for a steel containing .30 per cent. carbon, and point E for a steel containing .45 per cent. carbon. We are thus struck at once by the apparent law that the higher the amount of carbon the lower the temperature at which complete inter-diffusion with the associated ferrite occurs.

We know also from previous observations that a steel which contains .90 per cent. carbon consists entirely of pearlite, and is therefore completely inter-diffused as soon

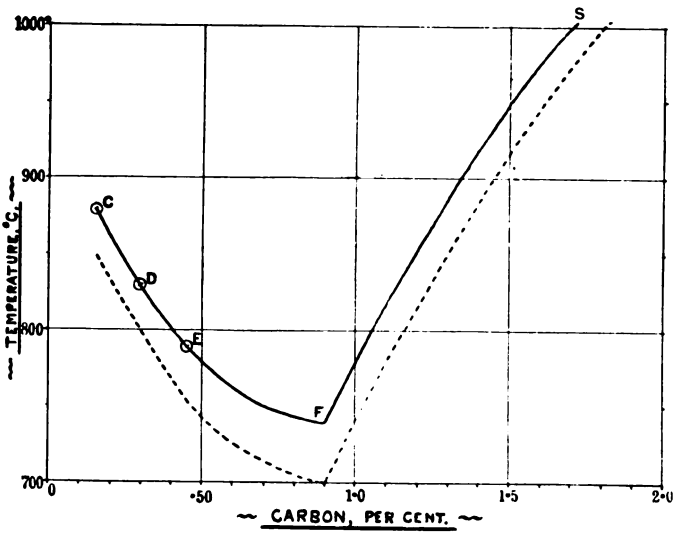

FIG. 54.—Equilibrium diagram.

as the pearlite transformation has taken place: this consideration fixes the point F at 740° C., and the line connecting the observed data turns out to be an approximately straight line C F extending from 740° C. to about 900° C., which indicates an important feature of the thermal behaviour of all carbon steels containing less than .90 per cent. of that element.

Steels which contain more than .90 per cent. carbon still consist largely of pearlite areas, but instead of being associated with ferrite (owing to excess of iron), they are now associated with free cementite (owing to excess of iron carbide). The pearlite transformations take place as before on heating to 740° C., and would therefore be represented

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in our diagram by the horizontal line through F ; and when thus transformed the inter-diffusion with free cementite occurs gradually as the temperature rises, and is completed at certain definite temperatures. By a similar series of observations, made in the same manner as before, but with greater difficulty, we note the temperature at which members of a series of high-carbon steels cease to contain undiffused cementite, and from the data construct a curve extending from F to S. The diagram now constructed is complete so

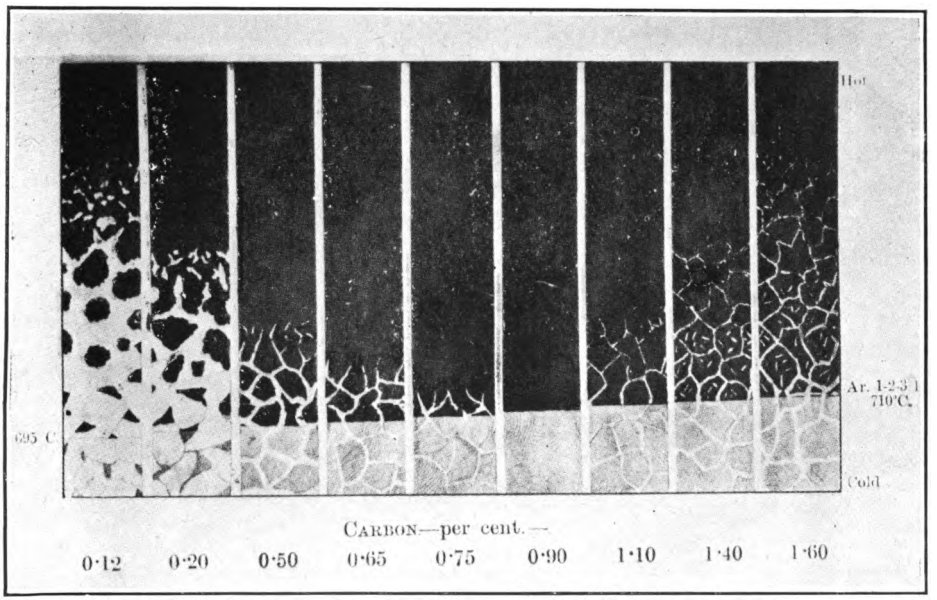

FIG. 55.—Mr. Stead's pictorial diagram.

far as the requirement of the case-hardener is concerned. It differs from the equilibrium diagram of scientific metallurgy in one respect only, *i.e.*, whereas the latter is constructed from data obtained on cooling, our diagram is constructed from data obtained on heating, and is on that account more generally useful for practical application to works purposes. The corresponding changes on heating and cooling are separated by a fairly constant temperature interval, as indicated by the fainter dotted cooling diagram in fig. 54.

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These considerations suggest that every piece of steel which has been rapidly quenched bears more or less clearly in its structure a record of the degree to which it has been heated and the rate at which it has been cooled. A number of thin strips of steel varying in carbon content between, say, .10 and 1.5 per cent. could in this sense be made to act as a pyrometer. And if the strips were arranged in an orderly manner after quenching from gradually increasing temperatures, their structures would present a series of pictures which, along the line of complete diffusion, would form a pictorial representation of the equilibrium diagram. This series of events has been recorded diagrammatically by Mr. Stead in fig. 55, which has been reproduced from one of his many excellent lectures, and it is recorded to some extent in every quenched specimen of case-hardened steel.

HELPFUL SCEPTICISM.

One result of arranging observed data systematically or diagrammatically, is to foster a helpful scepticism about many current statements. If the lowest temperature at which carbon (as carbide of iron) can diffuse or migrate is 740° C., then obviously there can be no special virtue in those hardening or case-hardening mixtures which are said to be operative at "scarcely visible redness." And the minimum temperature at which it is possible to produce certain effects, such, for example, as an outer casing containing 1.3 per cent. carbon, is fixed by laws quite outside the influence of Messrs. X. Y. and Co., who make none-such case-hardening compounds. It is not, of course, intended to suggest that one case-hardening compound is necessarily as good as another, and that cheap carbonaceous material like coke or anthracite coal cannot be improved upon: on the contrary, there are very wide differences in the behaviour of various carburising substances, but they succeed, if they do succeed, within the limits of temperature indicated in fig. 54. For a like reason, there appears to be also no scientific basis for the statement that particular kinds of steel, to the exclusion of others, can be most effectively case-hardened by some special kind of carburising compound.

Long before the iron-carbon equilibrium diagram was conceived, Caron, who was a close observer of cementing operations, had made up his mind that each particular temperature corresponds to a degree of saturation and rate of penetration. Whilst this appears to be true for some, and possibly for many, carburising reagents, there are apparent

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exceptions, so far at least as the degree of saturation is concerned.

When the carburisation extends over many days it is by no means unusual to find a greater amount of carbon on the extreme surface than can be accounted for by reference to the equilibrium diagram; the material illustrated in fig. 28 is an example of this apparent anomaly. A very likely explanation suggested by Charpy to account for such occurrences is the unavoidable variation in temperature during the prolonged heating. If, for example, at a steady temperature of 1,000° C. the surface of the steel is saturated in relation to free cementite, then a slight fall in temperature would cause part of the cementite to fall out of solution. When the temperature rises again, the precipitated cementite should be re-dissolved. But about every particle of the steel, as we may think, there are carburising gases which, if no precipitated cementite were present, would also quickly part with the amount of carbon needful to restore the percentage; and it becomes, therefore, a question whether the equilibrium can be restored more quickly by the carburising gases or by the precipitated cementite. If by the former, or if by the two jointly, as we think likely, then a part of the cementite remains undissolved, and the amount of it, by repeated variation in temperature, may become considerably more than would otherwise be possible.

As the combination between the carburising gases and the iron is of the nature of a chemical reaction, it will be influenced, as to its rapidity at any rate, by the composition of the gas, its pressure, its relative stability at a particular temperature, and so on; and in this sense the irregular behaviour mentioned in the two preceding paragraphs may be more marked with some cementing compositions than with others, *i.e.*, some compositions may introduce more carbon into the surface than others—more, indeed, than is theoretically possible on the assumption that the carburising temperature remains quite constant.

SOLID CARBURISERS.

The simplest carburising substance is pure carbon—it is also the most inefficient. It has been shown that a diamond (crystallised carbon) heated in vacuo in contact with iron will carburise it. Similar experiments have been made with other pure forms of carbon, and all of them undoubtedly carburise if pressed into actual contact with heated iron. But as actual contact carburisation with solid media, even

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if efficient, would be difficult, if not impracticable, such reagents are of no industrial importance. The cheapest of such solid media, coke and anthracite coal, are, therefore, useless, except as one of them (coke) may be used to increase the volume of a mixture, and act, on account of its porous nature, as a carrier of other substances.

DIAMONDS. Diamonds of very considerable value have been used to prove and confirm the statement that a pure solid form of carbon will carburise pure iron. Already in 1798 an observer named Clouet heated small diamonds in a crucible made from soft iron and produced globules of hardenable steel thereby. A year later the experiment was repeated with a similar result. In 1815 Pepys heated together diamond dust and iron wire to produce steel. A similar experiment was carried out in 1864 by Marguerite. Between 1888 and 1890 both Osmond and Roberts-Austen showed that diamond in contact with iron at temperatures between 1,000 and 1,100° C. would carburise even when gases of all kinds were excluded. Other observers were disposed to ascribe these positive results—when outside gases were excluded—to gases occluded in the iron which were liberated on heating in vacuo. The question was summarised by Guillet in 1910 as follows:

(1.) Carbon in vacuo cements only by direct contact.

(2.) If gases are present or can be evolved from the steel by heating. then cementation occurs without direct contact between solid carbon and the iron.

(3.) The carburising effect increases with gas pressure.

It is not to be assumed that any shop foreman will worry himself overmuch about diamond dust as a carburising reagent. But if such a one should desire to see how inefficient pure solid carbon would be if it could be pressed into actual contact with the metal, he need only make a few observations on a well annealed piece of a blackheart malleable casting. A piece of metal machined from such a casting consists of impure iron crystals (ferrite) in contact with small spheres of very finely divided graphite as seen in fig. 56. The contact between the iron and graphite is much more intimate than it could be made by any kind of packing in case-hardening boxes, but it will be found on reheating to carburising temperatures, and quenching, that the rate of cementation, *i.e.*, the re-combining of the free carbon and the surrounding

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iron with consequent hardening of the quenched piece, does not take place very quickly.

Solid carburisers may be used industrially only if gases are evolved from them on heating. The evolved gases are the actual carburisers, as may be demonstrated by packing the lower part of a short steel bar in sand and covering the upper face only with the carburiser, or by pumping out the evolved gases immediately they are formed. In the former case the steel bar will be carburised on all sides (see fig. 43), and in the latter case very little carburisation will have taken place. EVOLVED GASES.

It would appear, therefore, to be of first-rate interest to know what volumes of gases are evolved from a carburising mixture as its temperature rises, and what is the composition of such gases. Questions of this obvious kind can be answered only by laboratory experiments which require considerable skill and much patience, and very few results have yet been published. The most extended observations, so far as the writer knows, are those made by Nolly and Veyret,* who examined ten different cementing mixtures, and measured the volumes of gases evolved at each rise of 100° C. in temperatures up to 1,100° C. The materials examined were :

(1.) Pure wood-charcoal.

(2.) Wood-charcoal with 10 per cent. barium carbonate.

(3.) Wood-charcoal with 30 per cent. barium carbonate.

(4.) Wood-charcoal with 50 per cent. barium carbonate.

(5.) Wood-charcoal with 30 per cent. barium carbonate, charcoal having been previously heated up to 100° C. in a closed vessel.

(6.) As 5, with 50 per cent. barium carbonate.

(7.) Soot 20 per cent., plaster of Paris 40 per cent., ferro-cyanide 40 per cent.

(8.) Charcoal 20 per cent., salt 51 per cent., ferro-cyanide 23 per cent., moisture 6 per cent.

(9.) Horn and hair 20 per cent., vegetable fibre 50 per cent., soda ash 11 per cent., quartz or crushed firebrick 5 per cent., moisture 14 per cent.

(10.) Vegetable husks 70 per cent., soda ash 13 per cent., sand 3 per cent., moisture 14 per cent.

* Ferrum, 1913, and International Testing Association, New York, 1912.

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The relative volumes of gases liberated at various temperatures are shown in the following table. The second heating referred to in the table was made after the temperature of the heated materials had been allowed to sink to between 300° and 400° C.

The composition of the gases evolved at certain stages of the heating operation is also shown in tabular form.

ANALYSIS OF THE GASES EVOLVED AT DIFFERENT TEMPERATURES.

Mean Temperature of the Reagent at the moment when the gas was collected.		Carburising Reagent.				
		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.
From 15° to 300°	CO_2 ..	21.4	9.0	0.9	2.6	1.2
	O ...	14.8	17.8	19.1	20.0	16.6
	CO ..	5.3	3.1	1.0	1.2	3.6
	H ...	0	0.6	0	0	2.0
	CH_4 .	1.4	0	0	0.8	0
	N ...	57.8	69.8	79.0	75.4	76.6
850°	CO ..	11.3	28.1	25.3	30.8	42.2
	H ...	74.0	52.8	57.7	53.4	20.0
	CH_4 .	10.0	8.7	8.7	7.0	2.0
1050°	CO ..	19.6	37.3	56.1	63.8	71.7
	H ...	73.5	60.0	32.0	28.0	15.0
	CH_4 .	0.6	0.9	0.9	0.8	0.7

		No. 6.	No. 7.	No. 8.	No. 9.	No. 10.
From 15° to 300°	CO_2 ..	0.8	0	11.0	6.2	19.4
	O ...	19.4	17.0	17.4	17.0	14.2
	CO ..	1.8	2.6	0	0	0.8
	H ...	2.4	0.8	0	0	2.2
	CH_4 .	0	0	0	0	1.2
	N ...	75.6	79.8	71.6	76.5	62.2
850°	CO ..	28.4	29.4	50.4	54.5	51.2
	H ...	37.0	23.6	35.2	34.8	35.8
	CH_4 .	1.2	1.2	2.0	1.7	4.2
1050°	CO ..	75.2	55.6	23.2	36.8	64.2
	H ...	12.0	19.2	56.5	51.4	22.2
	CH_4 .	0.8	0.9	0.2	1.2	2.2

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RELATIVE VOLUME OF GASES LIBERATED.

Carburising Agent.	No. 1.		No. 2.		No. 3.		No. 4.		No. 5.	
Mean Temperature of Reagent.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.
100	18	,,	31	,,	28	,,	30	,,	21	,,
200	18	,,	19	,,	17	,,	20	,,	0	,,
300	6	,,	5	,,	8	,,	10	,,	0	,,
400	50	0	16	0	15	25	5	,,	6	,,
500	111	0	49	0	61	6	30	0	4	15
600	150	3	113	0	86	6	71	8	3	3
700	188	4	113	0	75	12	86	9	6	5
800	90	4	125	5	78	13	80	10	25	8
900	64	4	198	11	129	19	69	11	36	6
1000	63		180	13	63	36	78	39	70	26
1100	25	12	90	10	42	16	50	35	30	5

Carburising Agent.	No. 6.		No. 7.		No. 8.		No. 9.		No. 10.	
Mean Temperature of Reagent.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.	1st Heat.	2nd Heat.
100	18	,,	16	,,	25	,,	28	,,	25	,,
200	0	,,	10	,,	16	,,	30	,,	33	,,
300	0	,,	0	,,	0	,,	41	,,	100	,,
400	0	,,	0	14	11	,,	142	10	210	,,
500	0	0	6	5	10	6	256	0	100	,,
600	0	22	25	3	67	0	154	0	128	8
700	22	0	138	3	86	6	115	0	87	4
800	40	4	190	6	85	11	105	11	72	14
900	34	7	85	6	88	14	76	31	33	2
1000	115	35	24	5	74	12	66	34	31	10
1100	60	7	14	6	34	10	49	10	3	6

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USELESS GASES.

The analyses given do not represent the exact composition of the gases in direct contact with the carburising agent. Certain gaseous products will have condensed prior to the sampling, and other changes will also have taken place during the unavoidable cooling of the gases previous to analysis; but the information as far as it goes is instructive. It will be clear, for example, that those carburising reagents which evolve large quantities of gases before the minimum cementing temperature (say 800° C.) is reached do not derive any advantage thereby unless those gases are wholly or partly retained in the case-hardening box.

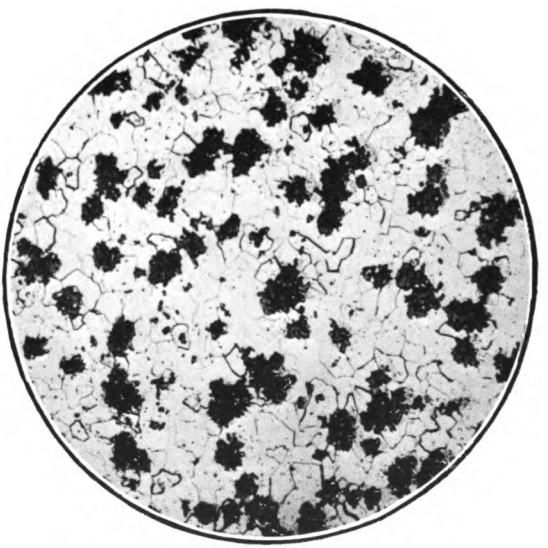

FIG. 56.—"Blackheart" malleable iron.

Carburising agents which contain moisture or raw animal or vegetable matter all evolve gases or vapours below red heat. The waste of gases which would probably be useful at higher temperatures need not be regretted, but such gases may be evolved explosively, and in any case are likely to disturb the luting of the boxes in making their escape. It is, therefore, advisable to adopt such mixtures as do not evolve large volumes of gases of which no use can be made. Volatile ingredients also absorb heat whilst they are being driven off, and thus lengthen the time necessary to bring the interior of the boxes to the desired temperature.

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In order to observe temperatures and the nature of the volatile constituents given off from heated carburising mixtures the arrangement sketched in fig. 57 may be used. It consists of a wrought iron, or, better still, a cold drawn steel tube of about 2in. internal diameter, which is closed at one end. Six or eight inches of its length is filled with a weighed amount of the mixture under examination, and then a fused silica tube of narrow bore is pressed into the centre of it and a perforated plug of ignited asbestos is placed into the tube to keep the mixture in position. The packed portion of the tube is arranged to lie entirely within the muffle, but raised from the bottom, of a gas-fired furnace. The fore end of the tube, which is hermetically sealed,

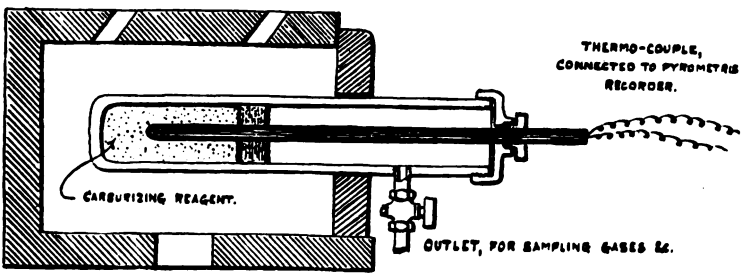

FIG. 57.—Arrangement for testing carburisers.

extends beyond the closed mouth of the muffle, and the arrangement is completed by a thermo-couple, which passes down the narrow silica tube and joins up to an autographic temperature recorder.

Samples of the gases liberated escape, or are withdrawn through the stop cock on the small lateral tube, and are collected for analysis. Through the same passage is also collected such ingredients as oil, vaseline, or other fatty substances, which vaporise near the closed end and condense again in the cool part of the tube. The temperature record enables variations in the composition of the gases to be plotted against temperatures at which certain constituents of the mixture are completely decomposed or vaporised. The jog, for example, at about 400° C. in the curve reproduced in fig. 58 indicates the temperature at which crude vaseline was driven off from a mixture of hydrocarbonated bone black, which is largely used in well-known British and American factories. Whatever advantage may be claimed for greasy

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carburisers of this kind, it is clear that most of the grease is wasted, and may damage the luting of the boxes long before a temperature is reached at which carburisation could take place.

DISCREPANCIES.

Some of the most mysterious discrepancies in the behaviour of the same material used by different operators arise no doubt from the varying degree of completeness with which case-hardening boxes are made gas-tight. In comparing the cementing power of two mixtures the results may be entirely contrary if the operation is carried out in an

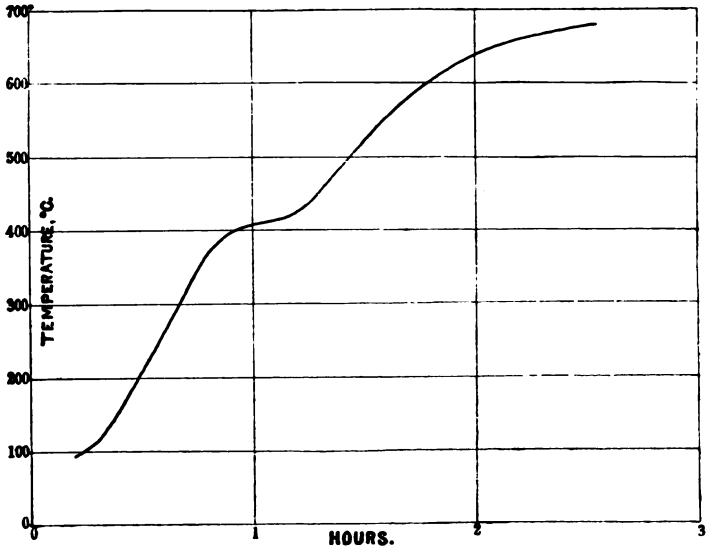

FIG. 58.—Heating curve of greasy bone black.

ordinary clay-luted box to what they would be if the operation were carried out, say, in a large wrought iron gas tube whose ends are closed with screwed caps. Comparative results which have been obtained at one temperature can also not be used to predict the results obtainable at a different temperature, nor does it follow that the relative behaviour of two materials used, say, for six hours at 900° C. will be preserved if the time is extended to twenty hours. These conclusions may be deduced from a study of the two tables on page 84, which show that carburising reagents become exhausted at different temperatures. Similar conclusions are supported by actual cementing observations: Consider, for example, the behaviour of the barium carbonate-

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charcoal mixture in comparison with burnt leather and with wood-charcoal. A time penetration curve made with these materials at a temperature of 900° C. is reproduced in fig. 59, and the barium-charcoal mixture is seen to less advantage for long exposures than for short exposures. For very long exposures wood-charcoal alone at temperatures of about 1,000° C. compares very favourably with any of the more complex proprietary mixtures.*

In addition to some form of charcoal—*i.e.*, charred wood, leather, or bone—the following substances occur as ingredients in carburising mixtures: common salt, sodium carbonate,

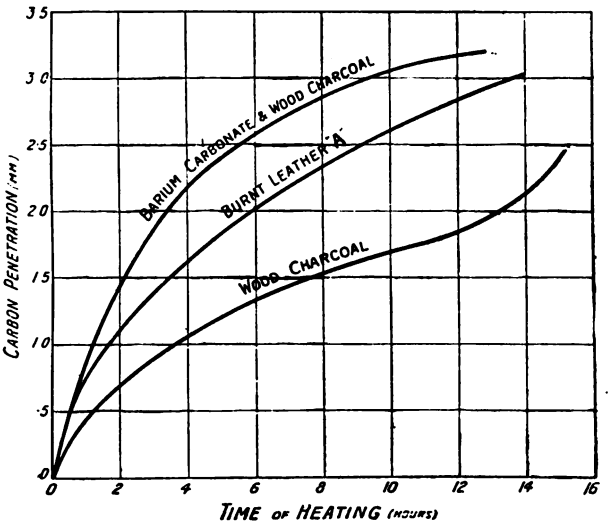

FIG. 59.—Time-penetration curves.

saltpetre, raw bone, resin, sawdust, soot, flour, potassium bichromate, ferrocyanide, hair or vegetable fibre, barium carbonate, limestone, various seed husks, heavy oils, petroleum residues, etc. It is difficult to realise that some of these ingredients are of any value, either directly or

* One reason possibly why so little is known about the reactions going on inside a case-hardening box is that carburising mixtures have been developed, as a trade monopoly, by people whose special knowledge, if they claimed to have any, was empirical and rule of thumb. Many manufacturers of carburisers have not been stimulated by ample criticism to an extended study of their own products, and are, in consequence, as dogmatic in their assertions as all are apt to be about subjects of commercial importance of which very little is generally known; the writer, as a manufacturer of carburising reagents, is speaking not entirely for himself.

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indirectly, as carburisers; others are costly out of all proportions to their usefulness; a few such as the alkaline carbonates have been found to lower the reacting temperature, and others, by distilling off volatile products at low temperatures, keep the surface of the cemented object white.

A GOOD CARBURISER

Carburising mixtures, though bought by weight, are used by volume, and too close insistence on economy in this respect is partly responsible for the use of fillers like sawdust and vegetable husks. A good mixture should be porous, so that the evolved gases may move freely around the steel objects; it should evolve carburising gases at the cementing temperature; it should not shrink unduly, otherwise slender objects, through lack of support, may lose their shape, and parts near the top of the box may, through exposure, be but imperfectly cemented; it should be a comparatively good conductor of heat, so that the temperature within the box may be as uniform as possible; it should not be dusty to the detriment of workmen handling it, and it should also pack firmly; thick oil is sometimes added for one or both these reasons. Some of these requirements are inconsistent amongst themselves, as, for example, porosity and high heat conductivity, but perfection is hardly attainable industrially, and compromise is a useful horse.

ALKALINE CHARCOAL.

Uniformity in behaviour under like conditions is a desirable feature of commercial carburising reagents. It can be ensured most completely in simple mixtures which do not evolve large volumes of gases below red heat, and the mixture should therefore contain only indispensable ingredients and, unless there is a good reason to the contrary, no raw animal or vegetable matter. Pure charcoal made from either wood or bone or leather, or mixtures of them, best answers this description, but the two former are not very effective at the lower temperatures of 850° C.–900° C. They are, however, much improved in this respect by the addition of alkaline carbonates, and the addition of either thirty to forty per cent. of barium carbonate or from six to eight per cent. of sodium carbonate—soda ash—will convert wood charcoal into a carburising reagent which compares very favourably with the more complex and expensive mixtures. Oak or beech wood charcoal is supposed to be superior to any other for carburising purposes, but the differences are not great compared with those due to the manner and extent of charring the wood.

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Objection to the use of charcoal-barium carbonate mixtures has been raised because the steel objects, when removed from the cementing mixture, do not possess a white untarnished surface. The colouration formed is quite unobjectionable, as it is not caused by any degree of oxidation whatever, but is due to the formation of amorphous carbon owing probably to the decomposition, in contact with metallic iron, of carbon monoxide liberated from the carburising mixture at temperatures below 800° C.* A thick hard layer of graphite would, of course, hinder the cementation, but such layers do not form under the ordinary conditions of use. The author is indebted to Mr. W. H. Dyson for the statement that the charcoal-barium carbonate mixture to which ten per cent. of sawdust has been added does not deposit graphite on the surface of the cemented articles; its addition, however, has no advantage save this doubtful one.

FIG. 60.—Phosphide blisters on cemented gear.

CHARRED BONE.

Charred bone is very widely used in large quantities both with and without admixture of thick oils. When bone charcoal is ignited, it leaves a residue or ash, consisting mainly of calcium phosphate equal to from fifty to eighty per cent. of its weight. Under the joint influence of the hot charcoal and iron, calcium phosphate may be reduced and part of the phosphorus it contains can then combine with the iron and form phosphide of iron, just as carbon can form carbide of iron, or sulphur, if present, would form sulphide of iron. Phosphide of iron is an extremely brittle substance: it has also a comparatively low melting point, and when it forms on the surface of cemented objects, it sometimes roughens them or even forms blisters as seen on the teeth of the wheel in fig. 60. Splinters taken from the surface

* According to Charpy the amorphous carbon is not deposited at temperatures above 850° C.

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of such an object were found to contain 2.5 per cent. phosphorus, and had the structure seen in the micro-photograph reproduced in fig. 61, which shows on the upper half the typical structure of iron phosphide, and on the lower half a normal cemented case containing free cementite, which indicates that the carburising operation had been carried out at a temperature not less than 1,000° C.

FIG. 61.—Microstructure of phosphide blister.

Large quantities of charred bone are used for cementing purposes, and it is not intended to suggest that its use should be discontinued. For anything the writer knows to the contrary, it may be superior to any other reagent for certain purposes, but it has the disadvantage of causing roughened surfaces if a deep penetration is required and a high temperature is used; and a roughened surface due to phosphide cementation will surely splinter during hardening or in subsequent use unless the phosphide skin happens to be ground clean away. According to R. R. Abbot (American Institute of Mining Engineers, October, 1912), of the one hundered thousand tons of carburising material sold in 1911 in the United States eighty-five per cent. were granulated bone

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Other objectionable substances which may be present in case-hardening powders are moisture and sulphur. It is said that moisture causes a roughening of the surface of carburised steel, but it is difficult, unless the moisture is associated with some other harmful ingredient, to understand how this occurs, because moisture is driven off and would escape from an ordinary box before the temperature of its contents can greatly exceed 100° C. (see fig. 41). It is, however, bad business to buy water at so much per hundredweight, and easy to see its objectionable features from that point of view.

Grayson* draws attention to the occurrence of sulphur in charred leather, and its diffusion into the surface of steel bars in amounts up to two per cent. The occurrence of sulphides is confined to the surface of the bars, and may penetrate no deeper than the small grinding allowance. But even if the sulphide globules do not cause the surface to remain soft, or the soft surface is completely removed by grinding, there is always the possibility that in the previous quenching small cracks may start from the sulphide inclusions and remain as cracks to worry an enquiring mind when the unsuspected source from which they sprung has been removed.

GASEOUS CARBURISERS.

Serious claims have been made for the use of gaseous carburisers pure and simple—coal gas or carbon monoxide being generally recommended. Experience, however, teaches that it is more convenient to generate a gaseous atmosphere in a box packed with a solid carburiser than to arrange pipes to lead the gas in and out of the carburising chamber. But the present advantage of the solid carburiser may be due mainly to furnace design, and gaseous carburisers are likely to be used more extensively in newly erected plant, because the use of gas is undoubtedly the easiest means of controlling variable conditions. Its use at present is confined to the carburisation of very small articles which can be shovelled into and raked out of a heated chamber without any fear of distortion, and to very large objects, such as armour plates, which it is worth while to handle singly. The use of gaseous carburisers is not exactly a novelty; oil gas was used for that kind of cementation in 1824 by Vismara, and coal gas in 1834 by MacIntosh. Even carbon-monoxide was used for cementation as early as 1851.

* Grayson. Iron and Steel Institute, 1910, No. 1, page 290.

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SPRINKLING POWDERS.

Carburisation by means of sprinkling powder and cyanide baths may be grouped together, as both processes are useful only when a very superficial layer needs to be case-hardened. Sprinkling powders are very useful in correcting superficial decarburisation of tools, notably large tools, such as press dies, which cannot be heated very quickly for hardening, and cannot always be entirely protected from an oxidising atmosphere. The powder is applied through a flour dredger, after the acting surface of the hot die has been cleaned with a wire brush, just prior to quenching. Sprinkling powders are usually mixtures of yellow prussiate of potash with various ingredients from amongst the following: Soot, horn-meal, resin, common salt, tartaric acid, tar and flour.

Potassium cyanide is not a desirable constituent of solid carburisers, as it is readily fusible and volatile at a red heat and extremely poisonous. It is used as a molten bath at temperatures between 750° C. and 800° C. for hardening very thin objects made from mild steel which require to have a hard surface, and which on account of their frailty or otherwise could not be carburised at high temperatures. The usual practice is to melt cyanide in a cast-iron pot and to replace the wastage with fresh cyanide or replace the old bath with an entirely new one when its carburising effect is no longer satisfactory.

When a fresh bath of cyanide has been prepared it very soon loses its strength at hardening temperatures whether objects are being hardened from it or not. At least seventy-five per cent. of the effective cyanide is destroyed (that is, decomposed) before or soon after the hardening temperature is reached. It is, therefore, more economical to prepare an ordinary salt bath from a mixture of sodium and potassium chlorides or sodium and potassium carbonates and add to the bath, just before using, ten per cent. of its weight of fairly pure potassium cyanide. As the fumes arising from cyanide baths are poisonous, every possible precaution should be taken to avoid personal injury.

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VIII.

METHODS OF TESTING.

THE case-hardener is not alone in requiring some simple means of testing the surface hardness of quenched steel articles. Out of every hundred operators ninety-nine use the file for this purpose, and it is doubtful whether any better kind of test is generally known. The hardened surfaces have usually to resist some kind of rubbing wear, and it is therefore reasonable to see to what extent they will withstand rubbing with a very hard and sharp substance. But a file must be used with discretion. Whether they are made by the same or different makers files are not all alike, either in respect to actual hardness or shape of teeth. The small triangular saw file is the most commendable, both for shape and uniformity.

HARDNESS: FILE TEST.

It is easy by means of the file test to determine whether or not an object has been hardened: a very poor file will serve that purpose. But it is not an easy matter to use a file, as files are frequently used, to determine the degree of hardness of hardened objects. A steel object must be very hard indeed if a good new file can make no impression on it, because files are made from steel which is quite as hardenable as the surfaces of the material being tested, and they have the advantage of possessing sharp cutting edges.

After the first stroke with a new file over a very hard surface the extreme edges of the teeth in action have become blunted either by actual wear or splintering, and on that place the file cannot be used again under quite the same conditions. The impression made by a file depends on the actual pressure applied in using it, also on the pressure per unit area tested, and this is subject to variation even when used by the same person. It is obvious, therefore, that the file test has its limitations even when an unlimited quantity of files of uniform qualities are available.

The file cannot generally be rubbed over the entire surface of a hardened object, and when it detects soft spots it does not indicate their extent in the same complete manner

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as the etching test (see page 43 and fig. 33), nor does it suggest any reason for the unexpected softness. But the file test is a useful one, and will be used and relied upon, in spite of its limitations, because of its extreme simplicity.

A very useful modification of the file test was brought to the author's notice by Mr. Geoffrey Barrett. It consists of a short bar of round steel, such as is used for making hardened balls, which after hardening is ground to a flat surface at one end. This provides a circular edge of definite diameter and a degree of sharpness and hardness which can always be reproduced. If the sharp edge is pushed, under slight pressure, over the hollow surface of a ball race, for example, it will detect a soft spot immediately and with much greater certainty than by the use of a file. Hardened bars of different diameter can be made for special purposes, and very small bars are especially useful for testing soft areas which have been previously disclosed by the etching test.

The most a file can do is to detect soft places; it can neither measure nor indicate in a reliable manner the difference in hardness between any two pieces from amongst a parcel of small objects which have been properly quenched from a temperature above the minimum hardening temperature. If a regular percentage of the goods hardened are rejected by the file test for apparent softness, the correct thing to do is to find out at once the cause from which the softness arises, and it will generally be found more to the purpose to look into the temperatures and conditions of hardening, and to spend money in controlling them, than to increase the severity of inspection and put up the file account.

SCLEROSCOPE.

The scleroscope, which is sometimes recommended as a substitute for the file, consists essentially of a graduated glass tube with an arrangement for releasing from the top of it, when in a vertical position, a hardened steel ball, or a hardened steel cylinder which is tapered and rounded at the lower end. The test is made by observing the height to which the ball rebounds after being allowed to fall on to the surface whose hardness is to be measured.

In measuring hardness by the scleroscope, one must assume that the surface of the object is uniformly hard, because a test is made of that small part only on which the ball falls, and the probability of detecting soft spots is not so great as with the file test. There are also two other objections to its regular use.

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The rebound of the hardened ball which falls on a relatively massive object is a measure of the speed with which the part deformed by the impact of the ball recovers its shape, and also of the degree to which the shape is deformed and recovered. These are not quite the properties which the case-hardener desires to measure, and the results, therefore, are only more or less related to the desired properties, and are comparable amongst themselves only so long as the materials tested are similar. The best known illustration of this limitation is the fact that rubber tested with the scleroscope gives a hardness figure as high as that given by annealed tool steel, and other soft substances, *i.e.*, soft to the mind of the case-hardener, like xylonite, give still higher figures.

If the object tested is not relatively massive, then part of the striking force is dissipated in moving the object bodily, and that part is lost so far as the rebound of the ball is concerned. This difficulty is lessened if the object tested is embedded in a block of pitch or sealing wax, but the test in that form is impracticable for repeated use in the workshop. It is also not quite satisfactory to clamp small articles in the vice, because even then, with some shapes at least, the hardness figure will vary, independent of the hardness, when the ball is allowed to fall on different parts.

The indentation made by a scleroscope hammer is very small, and the force exerted is confined almost to the extreme surface of the tested specimen. The test is, therefore, particularly useful for rapidly investigating the extent of surface softness arising from known causes of surface decarburisation. It will also, of course, detect surface softness arising from any other cause.

BALL TEST.

If the extent to which it is used may be accepted as the criterion of merit, then the ball test, known in England as the Brinell test, is the most satisfactory method for measuring the hardness of metals. But it may not be assumed that it is specially suitable for measuring the surface hardness of case-hardened steel.

The Brinell test is usually carried out by pressing a hardened steel ball 10 mm. in diameter under a load of 3,000 kgs. into the surface of the metal whose hardness is being measured. The permanent impression left in the metal on releasing the load will be greater or less, according to the resistance to permanent deformation which the metal offers, and this property, *i.e.*, resistance to deformation under

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prescribed conditions, is regarded as the basis of the test. The results are expressed in concrete figures, which are arrived at as follow : The form of impression is the segment of a sphere 10 mm. in diameter. It is, therefore, possible by measuring the diameter of the impression to calculate its area in square millimetres. This calculated area divided into the compressive force in kilogrammes gives the Brinell hardness numeral. These calculations have been made and collected in tables, from which, having observed the diameter of an impression, the hardness numeral can be at once read off. (See opposite page.)

In a modification of this test, known as the Ludwig cone test, a hardened steel cone is used instead of a ball, but the cone test cannot be usefully applied to hard steel. The ball test also becomes less satisfactory when applied to hardened surfaces for various reasons :

(1.) The impression is not truly the segment of a sphere, and the line of intersection on the surface tested is not a true circle.

(2.) The ball itself is also appreciably deformed about the point of contact.

(3.) The greater the hardness, the less the diameter of the impression, and of greater consequence, therefore, become the unavoidable errors of measurement.

In its application to case-hardened materials, the ball test is also limited by the fact that a plane surface is required for testing purposes, and such objects as round bars are excluded. It is also necessary that the thickness of the material tested should be at least several times greater than the depth of the impression, so that anything in the form of sheets can be brinelled only if several pieces are laid on each other, and then only with a rough approximation to accuracy if the metal is in the soft state.

The success of the ball test depends also on the assumption that the material tested is of uniform hardness so far, at least, as the immediate neighbourhood of the loaded ball is concerned, and this is precisely what case-hardened bars are not. The diameter of an impression made on a cased object would depend as much, at least, on the thickness of the cemented envelope as on its hardness. We are obliged, therefore, in these respects to correct the statement that "Brinell's pressure test may be manipulated by anyone without special practice and always with a true result."

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BRINELL'S HARDNESS-NUMBERS.

DIAMETER OF STEEL BALL = 10 MM.

Diameter of Ball Impression. mm.	Hardness Number for a Load of 3000 kgr.	Diameter of Ball Impression. mm.	Hardness Number for a Load of 3000 kgr.	Diameter of Ball Impression. mm.	Hardness Number for a Load of 3000 kgr.
2.40	652	3.80	255	5.15	134
2.45	627	3.85	248	5.20	131
2.50	600	3.90	241	5.25	128
2.55	578	3.95	235	5.30	126
2.60	555			5.35	124
2.65	532	4.0	228	5.40	121
2.70	512	4.05	223	5.45	118
2.75	495	4.10	217	5.50	116
2.80	477	4.15	212	5.55	114
2.85	460	4.20	207	5.60	112
2.90	444	4.25	202	5.65	109
2.95	430	4.30	196	5.70	107
		4.35	192	5.75	105
3.0	418	4.40	187	5.80	103
3.05	402	4.45	183	5.85	101
3.10	387	4.50	179	5.90	99
3.15	375	4.55	174	5.95	97
3.20	364	4.60	170		
3.25	351	4.65	166	6.0	95
3.30	340	4.70	163	6.05	94
3.35	332	4.75	159	6.10	92
3.40	321	4.80	156	6.15	90
3.45	311	4.85	153	6.20	89
3.50	302	4.90	149	6.25	87
3.55	293	4.95	146	6.30	86
3.60	286			6.35	84
3.65	277	5.0	143	6.40	82
3.70	269	5.05	140	6.45	81
3.75	262	5.10	137	6.50	80

The tensile strength of steel in tons per square inch is equal approximately to one-fourth of the Hardness numeral when the Brinell test is made transversely to the direction of rolling.

Perhaps it may be said that we have no means, of workshop value, for measuring the surface hardness of quenched steel which has been cemented to a depth of only 1 or 2 mm.; and that our best workshop methods of testing the general hardness is by means of a file. The file test, however, can be reasonably expected to determine only whether the hardening operation has been effective, and whether the surface is free from soft patches. In the latter respect it may be supplemented by the etching test, but a better guarantee for the production of good work than either can afford may be ensured by close attention to the preceding heat treatment operations.

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BRINELL MACHINE.

The mechanical properties of the core of case-hardened steels can be measured by the methods and apparatus generally used in testing structural materials. For this purpose the ball test, amongst others, is so very useful that we may consider ways and means of carrying it out. A form of apparatus suitable for the testing of small objects is illustrated in fig. 62. It consists of a hydraulic press acting downwards, the lower part of the piston being fitted with

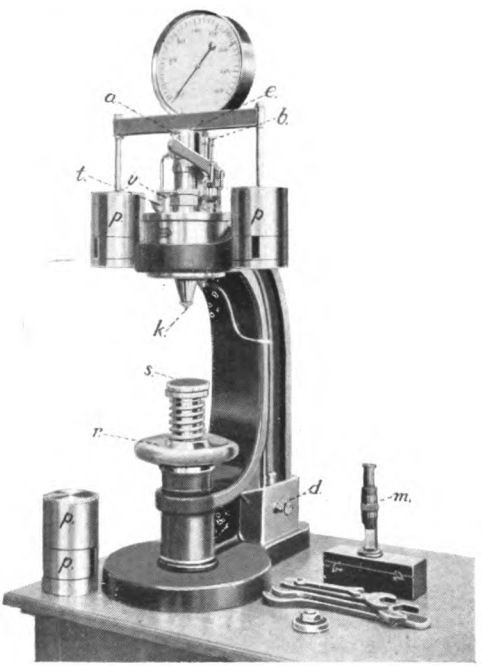

FIG. 62.—Brinell hardness-testing machine.

a 10 mm. steel ball K, by means of which the impression is made on the surface of the specimen or object to be tested. The sample is placed on the support S, which is vertically adjustable by means of the wheel R, and when the ball is pressed into it the load is indicated on the dial; at the same time the pressure can be controlled so as not to exceed the fixed amount required.

There are other kinds of machines controlled by strong springs or by loaded levers which permit of very rapid working, but particulars of these and many other forms can be

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obtained from trade catalogues. The test can be carried out comparatively without any special form of apparatus by merely placing a hardened steel ball between two specimens and squeezing them in a vice. If one of the specimens is a standard steel, it is easy, by comparing the magnitude of the impressions, to see whether the sample is harder or softer than the standard. A very handy holder for the ball when used in this way is described in the *American Machinist* (October 25th, 1913, page 587) and reproduced in fig. 63. The holder has a graduated scale on the lower part, so that the diameter of the two impressions can be actually measured. If a series of standard specimens are available this simple outfit can be made to serve a very useful purpose where no ball testing or tensile testing machine is available. As, however, it is not essential that the pressure should be applied between the jaws of a vice, but may consist of a sharp blow due to a falling weight or the blow of a hammer, it is possible to use the modified ball test on very large objects, or objects *in situ* to which the usual form of ball testing apparatus could not be applied.

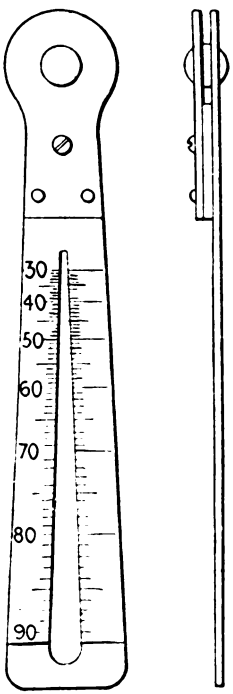

FIG. 63.—Ball holder for simplified form of Brinell test.

HARDNESS OF BAR STEEL.

The raw bar steel used for case-hardening purposes is required to possess certain mechanical properties. These can be fixed and controlled by chemical analysis and microscopic examinations, as indicated in previous pages. But even if these resources were always available the craftsman would occasionally desire some simpler and more direct means for determining what may be described as the hardness and toughness of the raw steel or of the core in the finally quenched object. The maximum stress and elongation of the material as measured on a tensile testing machine are supposed to correspond to hardness and toughness respectively, but for workshop purposes still simpler and, as regards toughness, more reliable means may be adopted.

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The Brinell hardness numeral has been found to bear a fairly constant relationship to the maximum stress (hardness) of forged or forged and annealed carbon steels. The relationship is sufficiently constant for shop control purposes at any rate, and is expressed as follows, on the assumption that the ball impression is made transversely to the direction of rolling:

Hardness numeral × .26 = tons per square inch.

i.e., if the hardness numeral, which can be determined with a Brinell machine in a few minutes, is multiplied by .26 the resulting figure will be the maximum stress in tons per square inch. The factor is reliable for material of approximately the same class so long as the yield point, or elastic limit, of the steel is not more than sixty to seventy per cent. of the maximum stress. But in quenched steels the ratio of the yield point to the maximum stress is higher and generally over seventy-five per cent., and in such cases the Brinell hardness numeral, being relatively greater, because a permanent indentation is not so easily formed, needs to be multiplied by the factor .25 in order to arrive at the approximate maximum stress of the material.

The suggested mode of testing can be used for workshop purposes by cutting off a few short lengths from various bars and brinelling them as received. Then submit a similar set of bars to all the forms of heat treatment, except actual cementation, to which the material will eventually be exposed, and again brinell them, in each case taking care before doing so to file or grind away the outer surface. These simple observations enable one to reject from a continuous supply of material those materials which are abnormal so far as hardness is concerned. The tests, on the quenched bars in particular, will detect unexpected variations, due either to differences in the amounts of carbon or manganese, or both, which the steel contains.

TOUGHNESS OF BAR STEEL.

The toughness of case-hardening steels cannot be determined so readily. It is certainly not determined by the ordinary forms of tensile testing either from the elongation per cent. or the reduction of area per cent., of which statement the figures given on page 62 stand as illustration. If by toughness we may understand the ability to resist fracture or cracking when suddenly distorted, then toughness must be measured by some form of shock test, and on the subject and value of shock testing there is, unfortunately, no great

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unanimity of opinion. It is, however, to some minds the test *par excellence* for structural steels, whether case-hardened or not, and merits, therefore, fair statement and careful consideration.

The impact shock test has for some years been discussed by testing associations and specially appointed committees notably in Germany and France, and also by international committees. Means of making the test have crystallised themselves into various forms of machines, of which the best

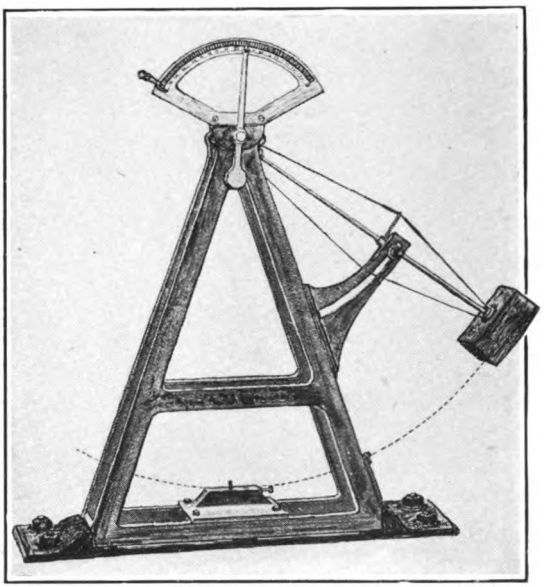

FIG. 64.—Izod impact testing machine.

known are those designed by Charpy, Fremont, and Guillery. The Izod machine is not so widely known, and has also not been developed and standardised to the same extent as the others mentioned, but it is extremely simple in construction and operation, and has special virtues of its own entitling it to a more extended use for works purposes.

IZOD IMPACT TESTER.

The general outline of the Izod machine is shown in fig. 64. It consists of a pendulum hammer, which, on falling from a certain height on the right-hand side, develops a definite amount of energy (say 100 to 150 ft.-lb.) by the time it reaches the vertical position. When no test piece is in

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the machine the hammer will rise on the left side to the same height as it fell from on the right, and the indicator moving over a graduated scale will show that no energy has been absorbed. When a test piece is gripped in the vice at the base of the machine the hammer cannot rise on the left-hand side until the test piece has been broken, and it will then rise owing to the energy developed by its fall less the amount of energy which has been used in breaking the test piece. The used energy will therefore, by suitable graduation, be read off directly from the pointer indicator, which is pushed along by the extended shaft of the rising pendulum hammer.

CONSTANTS OF IZOD MACHINE.

A test bar 10 mm. square, provided with a sharp "V" notch 2 mm. deep cut on the miller at an angle of 45°, is recommended for general purposes. The question of delicate refinements to control the sharpness of the "V" notch, which are often raised by way of objection to the test, are beside the mark, as we shall see later. The striking part of the hammer—a hardened and tempered steel edge—comes into contact with the test piece at a distance of 20 mm. above the bottom of the notch, and it is possible to make repeat tests from a bar for each inch and a quarter of its length.

The constants of the Izod machine are size of test piece, shape and depth of notch, and striking distance above the bottom of the notch. The special advantages of the machine are: (1) The possibility of making duplicate or triplicate tests on a test bar three or four inches long, which is a great and valuable convenience; and (2) the ease with which comparative tests along and across the direction of rolling (as indicated on page 29) can be made. By raising the vice so as to lessen the striking distance, such comparative tests can be made on test pieces whose lengths do not exceed one or one-and-a-quarter inches, *i.e.*, on test pieces cut at right angles to each other from gear wheels, rolled bars, etc.

The impact figure which it is suggested should be taken as an index of toughness is a measure of the energy required to break a bar provided with a "V" notch when struck with a hammer a certain distance above the notch (as represented diagrammatically in fig. 21). To simplify the matter, for consideration we may assume that the material being tested is practically uniform, *i.e.*, free from elongated slag streaks, cracks, and seams. It may also be assumed that the structure of the material is small compared with the

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size of the notch. This is actually so in forged or rolled material which has not been grievously overheated, but it is not true of large steel castings for example, and in such cases it makes a great difference to the result, whether the bottom of the notch falls on the junction line between one large crystal and another (as indicated in fig. 65) or on either side of it.

NOTCHES AND CRACKS.

When the pendulum hammer strikes the test piece the stress is concentrated about the base of the sharp notch and first starts a crack there, and then extends it across the bar.

FIG. 65.—Irregular impact figures are obtained from coarsely crystalline material according as the bottom of the notch falls on or on either side of a crystal junction. x 25.

If the test piece is made from material having a high elastic limit (or yield point) the crack may be started and extended across the bar without any appreciable deformation of the surrounding material. If, on the other hand, the yield point of the material is very low, it may not be possible either to start the crack or extend it without the surrounding material becoming very much deformed. This distortion uses up a certain amount of energy which cannot be separately determined, though it may be roughly estimated from the

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appearance of the fractured ends. The impact figure, therefore, includes the effort required—

(1.) To start and extend the crack.

(2.) To deform the material adjacent to the notch and crack.

The extent of the deformed material in the neighbourhood of the notch is seen, after previously polishing one side of the test piece, in the area of the polished side which is roughened or takes on a matt appearance. This is illustrated by fig. 66, which represents a very tough kind of steel that has been struck a blow insufficient to break it. The bottom of the notch, which was originally sharp, has been greatly extended, and immediately below it comes the distorted material due to extension, then a medium layer not greatly distorted, and on the underside, within the angle, the material distorted by compression.

In hardened steels the resistance to deformation is very great, and such materials always give low impact figures, because the individual crystals will not distort at all under a stress which is sufficiently great to start and propagate a crack through the test piece. On tempering a hardened steel which corresponds to a maximum stress of one hundred to one hundred and twenty tons with proportionately high yield point, there is no very marked improvement in the impact figure until the material becomes much softer, say sixty to eighty tons. From this point onwards the impact figure increases rapidly, and reaches a maximum when the tempering is done at a temperature just about or below the calescence change point (Ac1), *i.e.*, just below the temperature at which the piece would harden if quenched.

When the test piece is made from hardened material the fractured surface has a crystalline appearance; and all test pieces, whether hard or not, which give low impact figures exhibit a crystalline fracture for the simple reason that the crack has travelled along the crystalline boundaries. The hardened and tempered test piece from which a high impact figure is obtained breaks with a short grey fibrous fracture, and not, be it noted, because the inter-crystalline strength of the material has necessarily been increased, but mainly because the strength of the crystal itself has been diminished. The effort required to break apart the crystals in the very hard material was less than the effort required to deform them, whereas the effort required to break the crystals apart

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in the softer material is greater than the effort required to deform the crystal, and, in consequence, the crystal itself is stretched, and breaks with a grey fibrous appearance.

HIGH IMPACT FIGURES.

These considerations tend to show that in order to obtain high impact figures, *i.e.*, in order to increase the resistance of material to shock stress concentrated in a small area, we require either to increase the inter-crystalline cohesion or

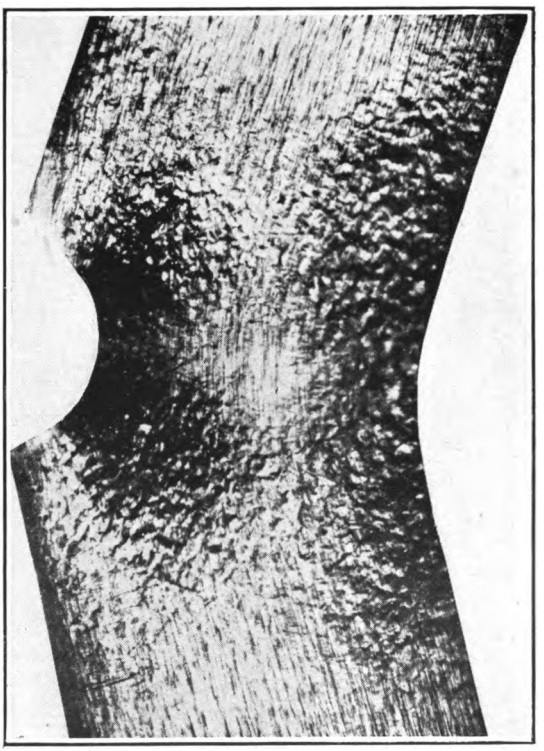

FIG. 66.—Distortion in impact test piece.

(and) to decrease the hardness of the material with the object of spreading the effects of the stress—as deformed material—over as great a bulk as possible. To increase the inter-crystalline cohesion we make the structure, that is to say, the individual crystals, as small as possible ; and to decrease the hardness of quenched material we reheat or temper at as high a temperature as possible consistent with the preservation of a structure of the same type.

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If, therefore, we are required to answer whether an impact figure of forty foot-pounds on a test bar of the dimensions given is a good figure or a bad one, we are obliged to ask what other mechanical properties in the material it is associated with. If it were associated with a maximum stress and yield point of about one hundred tons it would be extraordinarily good ; if with a maximum stress of sixty tons it would be moderate ; and if with a maximum stress of twenty or thirty tons it would be distinctly poorer than it need be. From this it will be seen that the impact figure does not bear any fixed relationship to the results of an ordinary tensile test. That fact, though it is the best criterion of its usefulness, accounts for the misunderstanding which delays the general adoption of the impact testing machine.

The strength of any metal or alloy depends on the hardness of the crystals and the cohesion between them. The former is controlled by composition and also by structure in so far as the same may be modified by hardening and tempering ; the latter depends on suitable heat treatment and mechanical work directed towards the production of small crystals instead of large ones. If with relatively great hardness there is associated a high impact figure, then clearly knowledge and skill have been exercised in the production of "quality" steel which can bear great stress without deforming, and if called upon to bear sudden stresses outside its compass will distort rather than snap asunder. On the other hand, if soft material is associated with a low impact figure, then either the crystalline grains are large or the structure of them, due to imperfect heat treatment or the want of heat treatment, is an undesirable one.

ROUND AND SHARP NOTCHES.

The bottom of the notch in the test bar may be rounded (as shown in fig. 65) instead of being sharp (as shown in fig. 21). In the former case an actual crack is not so readily started, and a greater part of the impact figure represents work done in distorting the surrounding material. The rounded notch, therefore, does not enable the brittleness of material to be presented in so striking a manner. But, as the impact figures increase, a larger and larger part of the material distorts before the fracture is completed, and a greater proportion of the impact figure is absorbed in this distortion until, when the impact figure is about sixty foot-pounds and over, it is not of great consequence whether a

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sharp or a rounded notch is used. This fact disposes of the objection relating to the difficulty of making a uniformly sharp notch if the object of the test is to control the quality of tough material such as is desired in the core of case hardened mild steel.

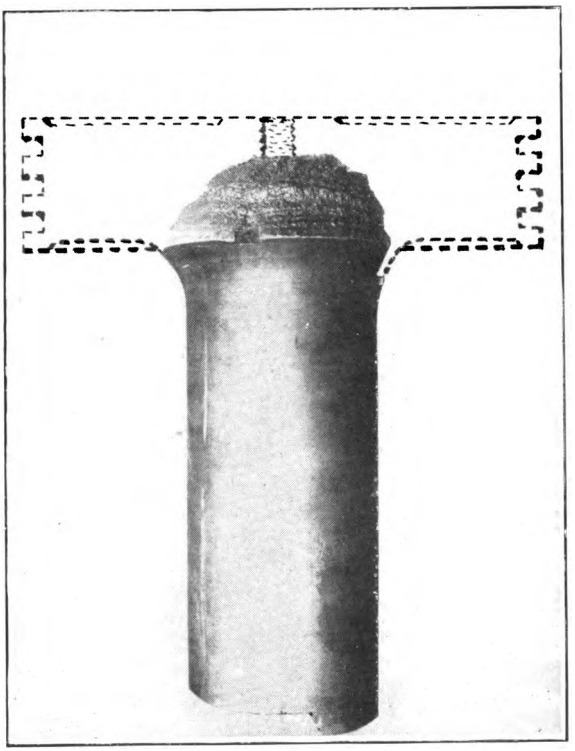

FIG. 67.—Fracture into piston head.

Objection has also been taken to the notch as a means of localising the shock stresses. It is true that articles in actual service are not intentionally notched, but it is also true that sudden changes in section producing sharp or more or less rounded corners are sometimes unavoidable; note, for example, the fracture through the piston head of a steam hammer represented in fig. 67. The tool marks on imperfectly finished surfaces are also notches of a kind, and act sometimes as starting points for a crack. Then there is

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the unavoidable bruising of surfaces in the wear and tear of everyday use, the occurrence of slag occlusions, and other kinds of surface defects, not wilfully produced but unpreventable, which suggest that the sharp notch in the test bar is not as remote as we would like to think from actual working conditions.

CREEPING CRACKS.

One of the main objects of case-hardening is to produce an article with a soft flexible core that shall withstand sudden stresses or repeated vibrations without developing cracks, and that shall resist the immediate extension of a crack which may be formed. For this reason the impact test would appear to be a most fit one. When an object, such as an axle, breaks in service it is generally found that the suddenness of the fracture, when independent of hidden flaws and the usual tensile properties, bears a close relationship to the values obtained from a notched bar impact test. If the impact value is high, the actual crack cannot so readily form, and when formed it cannot extend at once across the axle unless the factor of safety is very low. If it is not detected, and the axle remains in use, the crack opens and shuts when stressed and rubs itself smooth; when it extends further the new surfaces are again rubbed smooth, and so on, in a wave-like progression, the crack extends until too little of the sound material remains to support the load, and, finally, that breaks with a fibrous fracture, and presents a surface like fig. 68, in which the history of the crack's progress is clearly written. Such cracks, generally spoken of as "creeping cracks," are not often found in brittle material.

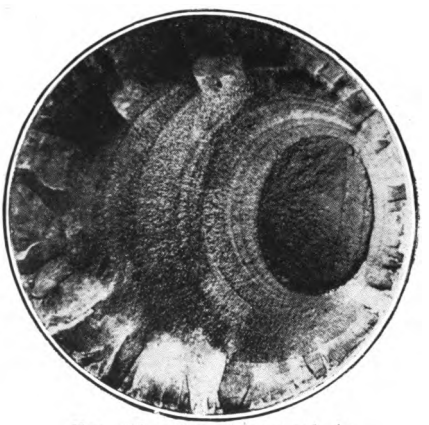

FIG. 68.—Creeping crack in waggon axle.

MAXIMUM TOUGHNESS

There are parts of a few machines which require to possess quite an extraordinary degree of toughness independent of the resistance they may offer to distortion. The case may be put quite simply by assuming that one end of a stiff bar

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is gripped in the vice and the free end is pushed backwards and forwards through, say, forty-five degrees without any regard to the force needed to deflect it through that angle. Hardened steel would break off at once; hardened and tempered steel would not last long; good wrought iron would do much better—better, in fact, than the mildest of ingot irons on account of its laminated structure and the consequent resistance to transverse cracking. When, therefore, there is unavoidable distortion due to forces which cannot or may not be resisted, the softest kind of iron treated so as to induce the highest attainable impact figure should be chosen. The best of such irons, no matter how sharp the notch may be made, cannot be broken by a single blow from a pendulum hammer.

These remarks on the general subject of hardness and toughness may be applied to the core of case-hardened steels in a few short paragraphs.

The ball test can be used to determine the hardness of the core with sufficient accuracy, and with less trouble and more instructively than the tensile test can be used to determine the maximum stress.

The impact figure is a better index of toughness than elongation or reduction of area per cent. It controls also the thoroughness of heat-treatment operations, and can be made on relatively small pieces of material. It also corresponds more closely to actual conditions of use.

For workshop control purposes it is not essential that a test bar should be actually cemented, but it should go otherwise through all the heat-treatment operations.

STRENGTH OF HARDENED CASE.

A method widely used for testing a case-hardened article —say a bar—as a whole is to bend it under a hand press and make certain empirical observations on the appearance of the fractured surfaces. As a means of breaking the bar, the hand press leaves much to be desired, *e.g.*, the time element is usually left to the operator. And as the operator may also be the responsible hardener, he is not anxious naturally to exhibit crystalline fractures if fibrous fractures are in demand. The appearance of the fracture will vary also with the temperature at which the bar is broken, either a crystalline or a fibrous fracture on certain materials being producible at will within a temperature range of less than 100° F. For the advantageous application of this and many other shop wrinkles the author is indebted to friends in the

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trade. The great deficiency of most hand presses is the want of a pressure gauge or some other means of showing the maximum pressure used before the first crack is started. This is surely of capital importance, because once the surface has cracked the useful life of an article is finished.

The effort needed to bend a case-hardened bar will depend on the thickness of the cemented case and the strength of the core, assuming that the case (hardened) is flawless to begin with. But the hardened case never is absolutely flawless, and the very conditions which heighten the appearance of fibre in the core, *i.e.*, seams and slag streaks of

FIG. 69.—Forces needed to break bars having crystalline and "fibrous" cores.

microscopic dimensions, as indicated on page 31, will act in the hard casing as starting points for a crack when the bar is bent under the press. This would be quickly realised if pressure gauges were in general use. In order to illustrate this point, two bars were prepared. One of them was notable for numerous fine slag streaks and seams, and the ease with which a fibrous fracture could be produced in it, the other was relatively free from these qualities (or defects as you please), and was rather the softer of the two. They broke when bent under the press with the fractures exhibited

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in fig. 69, the maximum load on the fibrous material being 8,300 kilogrammes and that on the finely crystalline material being 9,600 kilogrammes.

RING CRACKS.

It has been seriously stated, and it appears to be believed, that a series of ringed cracks in a bent case-hardened bar is evidence of good and accurate work, and, *per contra*, that a bar which does not show the series of ring cracks seen in fig. 70 has been incorrectly handled. The statement is at least misleading, and originated probably from some commercial gentleman who wished to impress his friends with the virtue of his wares. When a hardened steel bar is bent under a press it will crack first in that part which is most deflected; and if the bar is not artificially restrained, the crack first formed will widen considerably before a second or

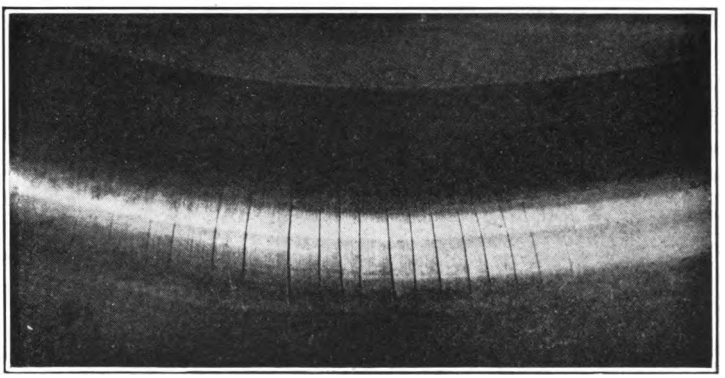

FIG. 70.—Ring cracks on bent case-hardened bar.

third ring crack can form. This procedure is not entirely dependent on the condition of the core. It is quite true that a fibrous or laminated core is favourable to the formation of ring cracks if the bending is done by blows from a hammer on a piece held in the vice; and the same effect can be produced with a press by applying force *seriatim* to various parts of the bar. But such a procedure does not test anything of real value; it merely satisfies a desire to produce an object which to the operator has a pleasing appearance.

NO TOUGHNESS WITHOUT DISTORTION.

We have seen already that a high impact figure, *i.e.*, resistance to fracture by sudden shock stresses, is obtained if the material which lies around an actual or incipient fracture becomes distorted; and that the energy required

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to bring about distortion is a very considerable part of the energy expended in causing fracture. But if the material about a notch is so restrained that it cannot distort under a blow, then the impact figure, one would think, would be much lower. The circumstances appear to be quite comparable with the catching of a cricket ball: in the first instance, where the hands are unconsciously withdrawn so as to bring the ball gradually to rest without personal injury; and, in the second case, where the hands are kept rigid and are severely punished.

In order, however, to express the general idea in concrete figures, two bars were prepared in the following manner: Bar A was 10 mm. square, and bar B was 12 mm. square.

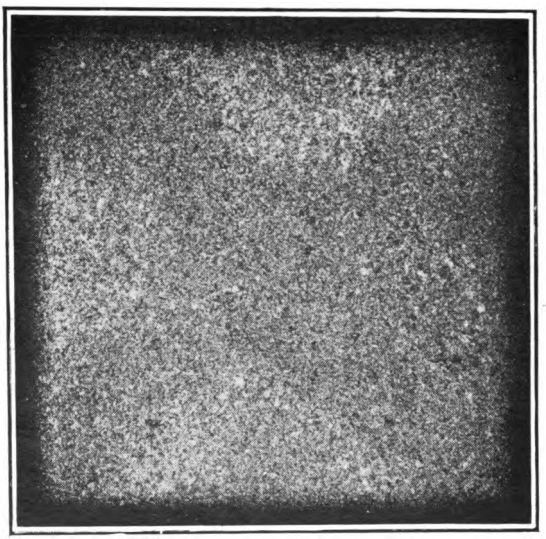

FIG. 71.—Section of cemented impact bar.

Both bars were cemented for three hours at 900° C., and submitted to double quenching at 950° and 780° C. respectively; 1 mm. was ground from each surface of the 12 mm. square bar B before the two bars were notched and tested. The results of impact testing were:

Bar A (cemented envelope) .. 9 and 10 ft.-lb.
Bar B (uncemented envelope) . 52 and 55 ft.-lb.

In order further to ensure that the condition of the material in bars A and B was identical, the cemented

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envelope of bar A was ground off and bar B reduced to the same size. On retesting the smaller bars thus produced the results were :

Bar A .. .. 40 and 40 ft.-lb.
Bar B .. .. 36 and 41 ft.-lb.

A cross section of bar A as tested in the first instance is reproduced in fig. 71.

The results appear to have a very considerable bearing on the behaviour of case-hardened bars, and they may be variously interpreted. It seems, however, justifiable to suspect that the claims made for extremely soft cores are often very much exaggerated, as such cores cannot exert a great resistance to fracture so long as they are restrained by the hardened case, and are only of doubtful or momentary value after the case has worn through or broken.

These results are of much wider interest than their application merely to case-hardened bars. They suggest that any form of test piece which can flow freely cannot reproduce the behaviour of similar material in large masses when the same is stressed locally and is not free to deform ; they explain also why such material regarded as tough may break short with apparent suddenness instead of elongating and otherwise distorting. We may, however, be certain that material which is free to distort (but does not) before a crack can be propagated through it is less satisfactory for structural purposes than material of equal hardness which, under like conditions of testing, will dissipate the energy of shock stresses by distorting freely ; but it is not equally clear how far the use of the tougher material is advantageous when it is restrained on every side by a glass-hard envelope.

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IX

AUTOMOBILE STEELS.

WHEN cast steel was first made, and for many generations afterwards, its "quality" was determined by the choice of raw materials which experience had shown would enable steel having the desired properties to be produced. A very important feature in the choice of materials was the degree of uniformity in successive supplies; this uniformity was indispensable because it was not clearly known which of the possible constituents were harmful, nor was it known how the amount of any such constituents could be determined. Swedish iron was uniformly good in this sense, hence its value as raw material and its almost exclusive use in Sheffield some fifty years ago for the manufacture of high-grade tool steel. But long after it became possible to make chemical analyses of steel with a fair degree of accuracy, the use of raw material according to brand or mark of origin persisted in spite of information disclosed by analysis. When, however, Bessemer's process of steel making was introduced, the adoption of chemical analysis for control purposes became indispensable, and from that time forward the suitability of steel for structural purposes, whether made by the Bessemer or open-hearth processes, has been determined, in the first instance, by its chemical composition.

CHEMICAL COMPOSITION.

For a generation or more the first question asked about material which had proved defective in later manufacturing operations or in use was: Is the chemical composition all right? And particularly the amounts of sulphur and phosphorus were scrutinised, as abnormal amounts of these were known to have led to trouble in the forge and mill. So much was thought of the composition as an index not only of the quality but also of the properties of steel that formulæ of various kinds were devised to express a relationship between the chemical analysis and the results which might be expected to accrue from tensile tests. Many a young enthusiast armed with the chemical analysis and a formula has set out to explain the properties of material in general or of some specimen in particular and covered himself with glory or otherwise. It had, of course, to be assumed that the tensile

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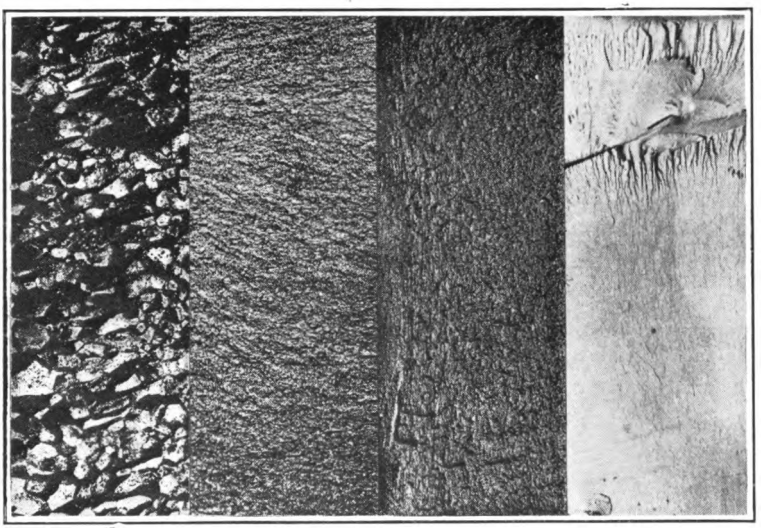
tests would be made on the steels in the natural state ; but as the " natural state " of a steel was (and still is) ill-defined, the difference between calculated and actual properties was often widely divergent.

For want of other forms of tests, which have since been supplied and developed by the microscope and metallographic methods, the value of ultimate chemical analysis assumed an importance to which it was not entitled, and persons well versed in the methods or results of analysis were assumed to occupy, or claimed to occupy, the position of an oracle on matters relating to steel and steel-making. Remnants of this erroneous and obsolete attitude can still be seen in



A B C D

FIG. 72.—Different fractures from the same steel.

specifications calling for material within narrow limits as to analysis, and ignoring those properties depending on manufacturing and subsequent thermal operations which are either not related at all to analytical results as usually expressed or related to them only in the sense that a well-constructed sentence is related to a dictionary.

PHYSICAL PROPERTIES.

Materials of the same ultimate chemical composition may differ enormously amongst themselves as castings, according to the melting process, casting temperature, mass and shape of material, rate of cooling, and so on ; and also as rolled

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bars of the same size even, in addition to the foregoing, according to rate of reheating and rolling, rolling temperatures, rate of cooling after rolling, and so on. Whilst, therefore, the chemical composition of steel is indispensable knowledge to the steel maker, it is no guarantee to the steel user that he has secured material having certain desired mechanical properties; and the knowledge is only useful to him at all if he knows how to utilise it in devising a scheme of heat treatment to which the material will be subsequently submitted. If no subsequent form of heat treatment is projected, then the user had better buy steel having the properties he wants, and leave the question of its composition to the steel maker.

As an example, of an exaggerated type, of the varied properties which may be associated with material of identical composition, reference may be made to fig. 72, which represents the appearance of fractures of the same kind of steel in the cast state A, cast and annealed state B, rolled and further heat-treated state C, and rolled and hardened state D. The mechanical properties of the material in these respective conditions are:

	Yield Point.	Max. Stress.	Elongation. 2″ × .564.	Reduction Area.	Impact Fig.	Brinell Hardness.
A. As cast and softened	—	30	.5	0	1	230
B. As cast and annealed	25	48	20	45	49	200
C. As rolled and heat-treated	50	60	25	63	55	260
D. Rolled and hardened	—	129	10	34	—	510

The figures are intended to indicate briefly that the chemical composition of a material, though of fundamental importance, is not a reliable guide to the mechanical properties which the material may possess, and they suggest further that the most comprehensive idea of the properties of structural materials will be based on an understanding of the changes which can be brought about in materials by systematic forms of heat treatment.

CHANGES BY HEAT TREATMENT.

If, for example, we accept acid open-hearth steel containing about .3 per cent. carbon as representing the material most largely used for machine-building purposes, we may

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determine, for a bar of given dimensions, the extreme degree of hardness and softness and other associated properties it is possible to induce in such material without altering its composition.

From what we know already of the ultimate structure of ordinary steels, it is obvious that the softest possible condition for all kinds of mild steel is attained when the pearlite areas are well laminated, and that is the case when the material, after forging, say, has cooled slowly through a range of temperature extending from 700° to 650° C. It is essential that the cooling should start from at least that temperature at which the pearlite areas are in the transformed (solid solution) state, but it is almost immaterial in ordinary carbon steel at what rate the cooling down to 700° and below 650° C. occurs. When the cooling takes place with such extreme slowness that the iron carbide does not form pearlite areas, but runs together in masses (as illustrated by figs. 45 and 46), then the material is still softer, as soft almost as pure iron, but also very brittle and not at all suitable for industrial purposes.

On the other hand, the piece of mild open-hearth steel is in its hardest attainable condition after heating to and quenching with the greatest possible speed from a temperature beyond that at which the transformed pearlite areas become diffused uniformly through the mass of the material. Very thin sections can be cooled almost instantaneously; thicker sections take a longer time, and the dissolved carbides cannot be preserved in a uniformly diffused state because the changes taking place in a cooling bar (as illustrated by figs. 12 to 15) occur rapidly. As the section of the bar increases, it becomes in a lesser degree possible to preserve a uniform distribution of the dissolved carbides, and also the carbides themselves begin to fall out of solution within their respective areas, until when the section is sufficiently large no practicable form of quenching confers any very appreciable hardness on it.

It is essential, therefore, if we would make comparisons between the properties of different materials, after the same or similar forms of thermal treatment, that a bar of some definite size should be chosen and adhered to. A round bar one inch in diameter is suitable for most purposes, and the results obtained from it may be used, with a few obvious modifications, to predict the properties of bars up to two inches

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in diameter which have undergone a similar treatment. In special steels where the critical thermal changes take place more slowly, results obtained on a one inch bar have a still wider range of application.

HIGH QUENCHING HEATS.

It may be not amiss to point out that when the components of a steel have become completely inter-diffused there is no advantage, with ordinary steels at least, in using a still higher hardening temperature with the idea of compensating for an increased bulk of material. There may, indeed, be a positive disadvantage in doing so: First, because the crystalline structure increases in size, and confers thereby undesirable brittleness; and, secondly, because the rate at which cooling will take place over the critical interval of temperature becomes actually slower. This latter feature is frequently overlooked, but it applies in all workshops where the cooling is done in a tank with a limited amount of liquid; that is to say, in most workshops. If, for example, a piece of one per cent. carbon tool steel is quenched from 800° C., nothing by way of hardening effect happens to it until the temperature reaches 700° C. or thereabouts, and then the total hardening producible occurs within a range of temperature covering only about 5° C.; after that range is passed the rate of cooling is only of importance as limiting the degree to which the hardened steel will be tempered. From 800° C. down to 700° C. the steel is losing heat to the quenching fluid. If we start from 900° C. instead of from 800° C., then twice as many heat units are absorbed by the cooling fluid *before* the steel reaches that range of temperature where the cooling fluid is required to act; and as the cooling fluid becomes hotter it is necessarily less active. This consideration applies especially to oil quenching because oils have a comparatively low specific heat and low heat conductivity, and are used always in limited amounts.

From a steel in the hardest possible condition a material less hard, but possessing other desirable properties in greater degree, can be obtained by reheating. The measured properties vary generally, but not always, in a fairly uniform manner as the reheating (*i.e.*, tempering) temperature increases. And the rate of cooling from the tempering heat is generally, but not always with special alloy steels, of very little consequence. If, therefore, a series of bars were water quenched and reheated to varying temperatures short of the calescence change point, the results of mechanical tests on

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such bars would include every possible condition of usefulness for machine building which could be got out of steel of the given composition; and a collection of such results would enable instructive comparisons to be made and facilitate the choice of material, both as to prime cost and ease of handling, for any particular purpose.

SERIES HEAT TREATMENTS.

The following results were obtained from sound pieces of acid open-hearth steel, containing carbon .30, silicon .11, manganese .60, sulphur .032, and phosphorus .024 per cent. The pieces treated were one inch round bars seven inches long. These were all quenched in water from 850° C., and afterwards reheated to the indicated temperatures for one hour and allowed to cool off in the air:

Reheating Temperature.	Yield Point.	Max. Stress.	Elongation. 2″ × .564.	Reduction Area.	Impact. ft. lbs.
As hardened	—	50.5	16.8	—	24
100° C.	—	49.6	18.5	—	33
200° C.	—	49.4	20.0	—	39
300° C.	32.6	47.1	22.5	47.1	42
400° C.	34.8	50.1	18.0	44.5	36
500° C.	33.7	46.8	24.7	59.2	76
600° C.	25.6	41.9	28.0	63.6	86
700° C.	25.1	36.3	30.5	65.8	95
750° C.	25.0	33.8	30.0	51.0	75
800° C.	23.1	34.4	30.0	52.2	57
850° C.	21.1	34.2	30.0	52.2	50

The curves in fig. 73 are plotted from these figures, and bring out a number of relationships, already more or less well known, which apply to similar series of heat treatment observations made on any kind of steel whatever. In order to illustrate the following remarks completely we include also in fig. 74 the mechanical properties of a heat-treated series of nickel-chromium steel.

The maximum stress and yield point fall and the elongation and reduction of area rise as the reheating (tempering) temperature is increased. The mild steel (fig. 73) exhibits a strange exception to this rule (which was first observed by E. A. Deakin) at a temperature of about 400° C. At this temperature the material is actually harder than it was after reheating to a lower temperature. This irregularity occurs in carbon steels with unequal distinctness; it is said to occur in nickel steels, but if so it must be to a much less extent; it does not occur, so far as the author knows, in the more complex alloy steels.

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The yield point and maximum stress of the reheated materials bear a fairly constant ratio to each other, and the curves representing them run approximately parallel (fig. 74) so long as the reheating temperature is well below the hardening range. When the hardening range of temperature is entered, but not actually exceeded, the curves representing maximum stress and yield point diverge from each other, and both the elongation and the impact figure fall. This is especially noticeable in all kinds of air-hardening steels.

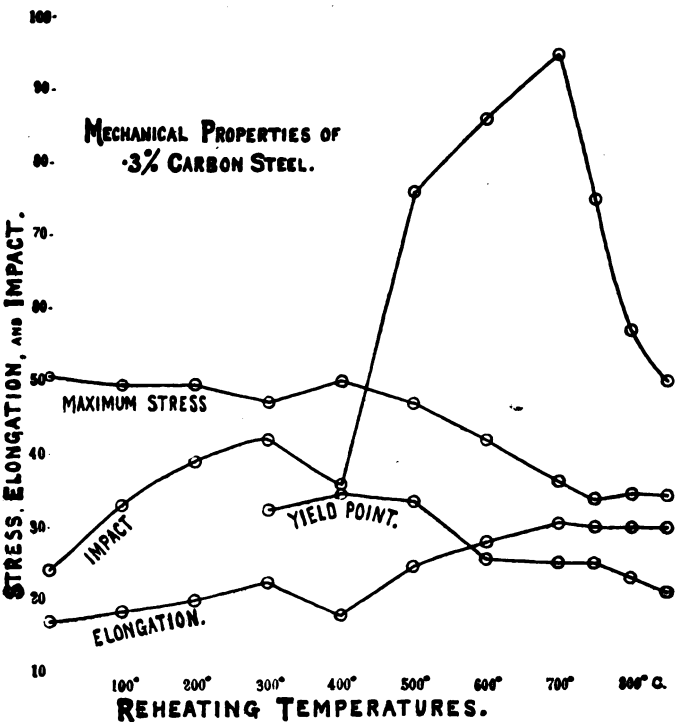

FIG. 73.—Mechanical properties of mild steel after different forms of heat treatment.

TEMPERING ALLOY STEELS.

In nickel-chromium air-hardening steels the reheating temperature for softening may not be pushed right up to the calescence change point as observed by the usual thermo-couple methods. Unlike ordinary carbon steel, the hardened nickel-chrome steels on reheating do not become gradually softer and softer until (with an additional rise in the reheating temperature of about 5° C.) they pass at once from the

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very soft to the very hard condition. On the contrary, after passing a reheating temperature (about 660° C.), which induces the maximum softness that can be attained by tempering, the steel, reheated to higher temperatures and quickly cooled, becomes gradually harder some 40° or 50° C. before it reaches full hardness. The comparative behaviour of

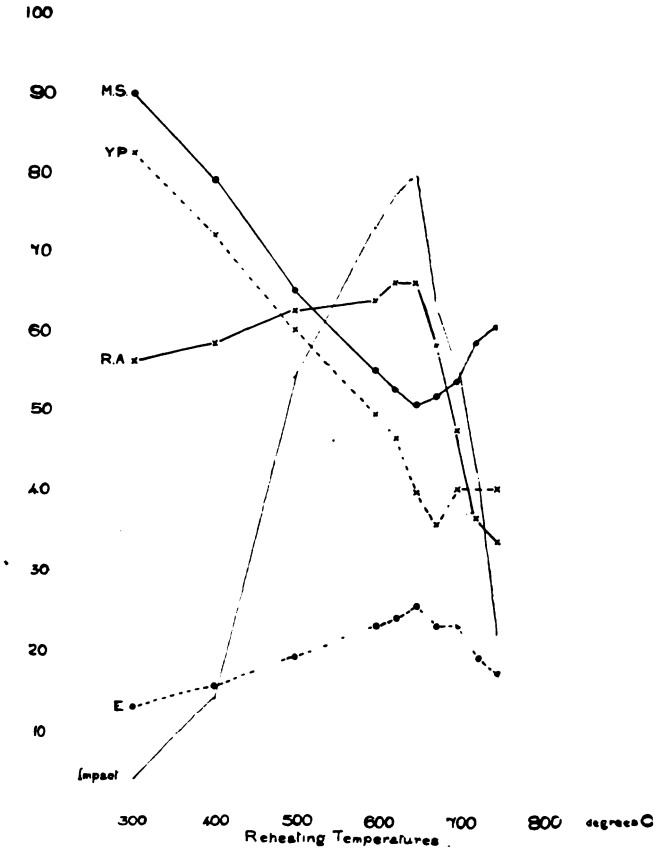

FIG. 74.—Mechanical properties of nickel-chrome steel after different forms of heat treatment.

carbon steel and nickel-chromium steel when tempered is illustrated diagrammatically in fig. 75. Unless followed by slow cooling or some other form of heat treatment, the alloy steels should not be treated within that range of temperature which enables them to become harder and not fully hardened when subsequently cooled, as such treatment invariably

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lowers the yield point very markedly, raises the maximum stress somewhat, lessens the reduction of area, and spoils the impact figure. These variations of mechanical properties in the range of temperature between 650° C. and 750° C. are a very sensitive index of the treatment, and may sometimes be used, when no other means are available, for determining the treatment to which a piece of steel has been exposed.

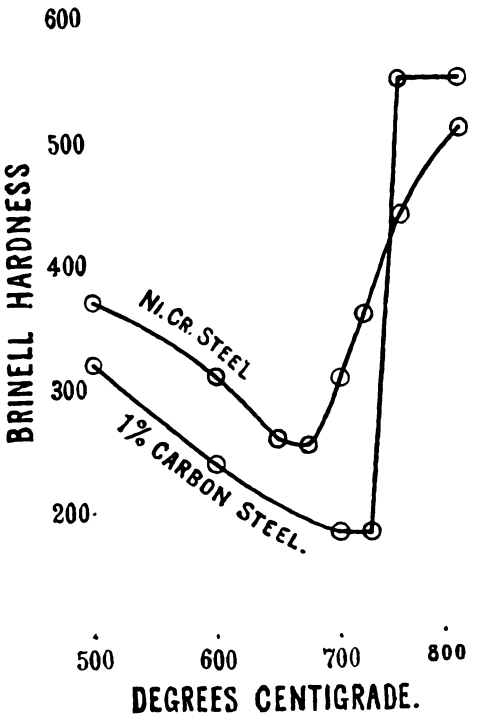

FIG. 75.—Comparative behaviour on tempering of carbon steel and nickel-chrome steel.

BUYING MECHANICAL PROPERTIES.

If an orderly arrangement, say, according to chemical composition, be made of the mechanical properties of as many distinct kinds of steel as may be found in commerce, after the same have been submitted to a series heat treatment, then we find identical mechanical properties in materials differing very widely in chemical composition, and we find also (as illustrated by the table on page 76, and figs. 73 and 74) that the same material may possess a varied and extremely wide range of mechanical properties, according to the kind of heat treatment it has received.

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The chemical composition of steel may mean little or much, depending on the extreme mechanical properties to be associated with it. Taken by itself it indicates a possibility. But no kind of steel is of much consequence unless it has been made and cast in a workmanlike fashion and then heat treated so as to induce in it the properties required for its purpose. The machine builder, therefore, who buys "steel" for immediate use without any regard to the thermal treatment it has received is taking a risk; whereas if he buys material having a certain composition with the intention of heat treating it he accepts responsibility for the mishaps incidental to heat treatment, and must assume also some knowledge of the operations and limitations of steel making. In making the smaller parts of aeroplanes, such as strainers and turnbuckles, it is frequently stipulated that the parts must be machined from heat-treated bars, and no heat treatment of the machined objects is permitted, *i.e.*, the machinist buys material having certain properties without any regard to its composition, and cuts it to the required shape. This feature of a specification is likely to commend itself to other branches of engineering, because it simplifies inspection and minimises disputes about defective goods. It also leaves the heat treatment operations in the hands of the steel maker, whose particular business it is, or should be, to carry them out in a thoroughly efficient and scientific manner.

But, no matter where the heat treatment operations are carried out, the builder of automobiles or of other machines requires ultimately to have certain dependable properties in the various parts of the machines, and should be interested in any simple rules which may be useful guides in the selection of the materials.

SELECTION OF MATERIALS.

A rule to which there are no exceptions is this: Of two pieces of the same material equally soft, that piece is best able to resist stresses of all kinds which is in the hardened and tempered state. In terms of structure, this means that a steel whose components are distinctly separated from each other is inferior to the same steel in which the components have been completely inter-diffused by heating to a suitable temperature and trapped in this state on quenching, followed by reheating so as to produce the required degree of softness. This rule is illustrated by the table on page 121. On comparing the mechanical properties of the piece normalised by reheating to 850° C. with the piece which has been tempered

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by reheating to 700° C., the former is seen to be inferior in every respect, and the inferiority would be still marked if the comparison were made with a forged bar, equally marked if the bar had been annealed, and still more marked if the bar had been overheated, though in each case the maximum stress and elongation, which are often erroneously accepted as an indication of quality, would not vary very much.

A second rule to which there are few exceptions is that the composition of the steel should be so chosen as to yield the required degree of hardness after hardening and reheating to a temperature not far below the hardening range of temperature. To turn again to the table on page 121, we see that ordinary mild steel of about .30 per cent. carbon, in the form of objects which are comparable in size with a one inch bar, can be made to possess any degree of hardness between the tensile limits of 30 and 50 tons. But the most useful range of tensile properties for this material is between 35 and 45 tons, because within these limits every other desirable property of the material is simultaneously good. If steel with a tensile strength of 50 to 55 tons is required, it is very much better to start with a steel which can be hardened more intensively, and then, by reheating to a suitable temperature, softened to the required degree. This consideration raises at once the question as to what advantages can be secured by adding various substances to mild steel.

CARBON STEELS.

The cheapest way of securing greater hardness is to increase the amount of carbon in the steel. By this means the tensile strength per square inch of a one inch bar of Siemens steel may reach as much as one hundred tons; but it is too brittle in that state for structural purposes, and the limitations of the material are two-fold. In the first place, the amount of carbon cannot be advantageously added in amounts beyond .80 per cent. or .90 per cent., and, secondly, the general mechanical properties when the quenched bar has been softened to give a tensile of about fifty tons are not much better than those attainable from a milder steel which after quenching has been reheated to a lower temperature: *e.g.*, in the comparative figures given on the following page the .30 per cent. carbon steel was not reheated after quenching, the .41 per cent. carbon steel was reheated to 600° C., and the .55 per cent. carbon steel was reheated to a temperature of 650° C.

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The addition of manganese to a certain extent may replace carbon as a hardener of steel, but its addition in amounts exceeding one per cent. if the amount of carbon is .5 per cent. or over, or one and a half to two per cent. if the amount of carbon is .30 per cent. or less, is not advantageous. Within these limits it is sometimes a safer

Carbon, per cent.	.30	.41	.55
Yield point tons per square inch	29.9	32.8	31.5
Maximum stress tons per square inch ..	48.9	47.3	47.9
Elongation per cent. on 2″ × .564	20.0	24.5	24.0
Reduction of area, per cent.	49.7	61.0	60.0
Impact figure (foot lbs.)	24	30	30

element to add than carbon, particularly if the objects are of great bulk. Manganese enables the quenching effect to penetrate deeper, and its presence, therefore, enables a large bar to be hardened to the core which if made otherwise from a higher carbon steel could be hardened on and only a small distance below the surface. Manganese steels as a separate class are not likely to be especially serviceable as automobile steels, but the element manganese, like silicon, is a very useful adjunct to both ordinary steels and special alloy steels. These remarks are not intended to refer to those steels containing from ten to fifteen per cent. of manganese, which are extremely tough and ductile, but are commercially unmachinable, and may be used to a limited extent only as castings or as simple forgings.

NICKEL STEELS.

The most serviceable alloying elements so far as structural steel is concerned are nickel and chromium. It is not the author's intention to discuss the metallurgy of these steels, but rather to indicate in what respects they are worth their increased cost. When nickel is added to ordinary mild steel it increases the actual hardness of the quenched material, and also increases the depth to which the hardening effect penetrates. Both these advantages are modified but not lost when the hardened steel is softened by tempering. This is made plain by comparing either of the carbon steels in the previous table with a mild nickel steel containing three and a half per cent. of nickel which had been quenched and reheated to 600° C. in order to bring the tensile strength down to about 50 tons.

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With the same maximum stress the elastic ratio is increased from seventy to eighty-four per cent., and both the reduction of area and the impact figure are higher.

	Carbon Steel.	Nickel Steel.
Yield point tons per square inch ..	32.8	42.0
Maximum stress tons per square inch ..	47.3	50.1
Elongation per cent. on 2″ × .564 ..	24.5	24.5
Reduction of area per cent.	61.0	63.2
Impact figure (foot lbs.)	30	70

In the same way, chromium, like nickel, increases the intensity of the quenching effect, and it might be shown that chromium steels, by suitable reheating, can be brought within any desired range of tensile strength with an all-round improvement in the other mechanical properties when compared with ordinary carbon steels. Chromium steels compare very favourably with nickel steels for straightforward constructional uses, but it would be foolish to push the comparison too far, as the properties of the two kinds of steel are by no means identical; in certain respects they are complementary.

NICKEL-CHROME STEELS.

From a machine designer's or builder's point of view, there is no structural steel known which has the same range of potential properties as nickel-chrome steel. One and the same steel by appropriate heat treatment may give either one or the other of the following test results, and a great variety of intermediate conditions as desired, according to the reheating (tempering) temperature chosen or the rate of cooling permitted during annealing:

	Hardest.	Softest.
Yield point tons per square inch	—	25
Maximum stress tons per square inches ..	130	42
Elongation per cent. (2″ × .564)	10	30
Reduction of area per cent.	35	66
Impact figure (foot lbs.)	3	90
Brinell hardness	520	160

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Each element added singly will increase both the hardening effect of quenching and the toughness of the reheated material, of any particular tonnage, as measured by the impact figure or any other means of gauging the resistance of the material under sudden stresses. The distinguishing feature of chromium is that it confers air-hardening properties on nickel steels when the material is cooled from moderate temperatures.

The advantages of a steel having air-hardening properties are two-fold. The fact that the steel is air-hardening means that comparatively slow rates of cooling from a suitable heat will cause the material to harden, and this enables objects having large dimensions to be hardened throughout either by quenching in air, oil, or water, as may be necessary to complete the cooling within the allowable time limit. Also, the slower the rate of cooling, the more uniform the rate of cooling becomes in the various parts of an object, and the less danger therefore arises of warping and cracking. A further advantage in small objects, or simple shapes like bars, is that they are necessarily hardened after the forging, rolling, or stamping operation, and in many cases at least they need only be reheated to induce in them the excellent properties of hardened and tempered steels.

SKILFUL HANDLING.

But these great advantages can only be fully realised if the material is skilfully handled, and they must not be pushed to extremes. If a steel has air-hardening properties, then it is hard in the ingot and billet form, and in every other form after hot-working from temperatures above, say, 800° C.; consequently it must be handled throughout with the care generally bestowed on hardened steel. Rapid reheating may crack it either internally or externally. Sharp corners are a source of weakness; and gussets cut into a crank axle, for example, may cause the forging to break by such an astonishingly simple accident as dropping it on the floor.

With structural steels, as with tool steels, the ultimate value of the objects made from them depends quite as much on the manner in which they are worked up into the finished shape as on the material from which they are made. The skill and knowledge of the workman must, therefore, always be taken into account, and if for any reason whatever these cannot be relied upon, then the extra cost of special alloy steels will not be reflected in the quality and reliability of

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the automobile. The supreme value of the material (having chosen the right material) depends on the manner in which it is heat treated; and methods of temperature control and other facilities often regarded as extravagant equipment will be needed to assist the workman, however highly skilled he may be.

It must also not be presumed that it would be all saving and no loss to buy only one kind of special structural steel and treat it according to its intended purpose, so as to produce very hard or very soft steel at will. Slavish adherence to such a course would undoubtedly, owing to complexities of treatment and the increase of wasters, throw the balance of advantage on the wrong side. The guiding principle, however, should be this—to choose an air-hardening nickel-chrome steel which on hardening will give the required properties after being exposed to the highest (tempering) reheating temperature; and this in general terms means that a good alloy steel can be used for purposes requiring variations of from twenty to thirty tons in tensile strength.

The mechanical properties of the three kinds of steel already considered are compared in the following table. The carbon steel and the nickel steel were water quenched, the nickel chrome steel was air-hardened, and all the steels were reheated to temperatures lying between 650° and 700° C.:

	Carbon.	Nickel.	Nickel-Chrome.
Yield point tons per square inch ..	32.8	42.0	40.0
Maximum stress tons per sq. inch..	47.3	50.1	51.0
Elongation per cent on 2″ × .564 ..	24.5	24.5	24.2
Reduction of area per cent. ..	41.0	63.2	63.6
Impact figure (foot lbs.)	30	70	85

VANADIUM STEELS.

What has been said already about chromium steels applies also to chrome-vanadium steels. They are inferior to nickel-chrome steel, in so far at least as they do not possess air-hardening properties which can be utilised commercially. They are assumed to be superior to chromium steels of a like kind to which no vanadium has been added, but the author has not been able to convince himself that the assumption is warranted, nor is he acquainted with any published results, amongst the large numbers which are continually

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being published, which confirm the assumption in a convincing manner. That vanadium added to steel acts as a "scavenger" may be admitted, but so also do manganese and silicon and aluminium, which cost the steel maker comparatively little, except the knowledge of how to use them to good purpose, and they cost the steel user nothing. However, it is not intended to raise commercial questions or to spend time in discussing negative results; those who are disposed to use chrome-vanadium steels may convince themselves at their leisure of the value of the added vanadium or continue without question to pay for its use as they choose.

The names of a number of elements are associated with steels in which they do not exist. Titanium steels, for example, do not usually contain a determinable amount of titanium, and boron steels do not contain boron, nor do tantalum steels contain tantalum, or if either of these elements are present in steel, the less of them the better. Uranium steels are also repeatedly mentioned, but are rarely obtainable in amounts sufficient to make a heat treatment series of tests.

It is quite possible that an element when added singly to ordinary carbon steel might deteriorate its quality, whereas if added in conjunction with a second element its influence would be distinctly favourable. But it is not usually the case, and one is justified in being wisely sceptical about double-barrelled steels when a high-price element, present only in small amounts, has no pretensions of its own worth talking about. It may be good business to parade such an element in company with powerful additions like chromium or nickel, but the forced relationship is not interesting to the student of metallurgy.

AIR-HARDENING.

Air-hardening steels, apart from the excellent mechanical properties which may be induced in them, are of great interest to the student of steel-hardening problems. It is well known that a piece of ordinary carbon steel on cooling from above the hardening range of temperature loses heat, at a uniform rate, for a while and then ceases to lose heat for a short period or even gets hotter.* This recalescence of

* The contraction in volume which accompanies this change can be made visible by passing an electric current through a piece of ten to twelve gauge wire which hangs loosely between two terminals about a metre apart. As the temperature increases on heating the wire sags, stops at about 750° C., and sags again. On cooling the wire gets shorter until its temperature reaches 650-700° C., then it suddenly sags and afterwards continues to shorten.

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the steel corresponds with the formation of separate laminæ of iron and carbide of iron (see figs. 2 and 15) which have previously been inter-diffused or dissolved in each other, *i.e.*, it is the latent heat of solution, and, though happening in the solid state, is comparable with the better-known latent heat of steam.

The rate of cooling and the recalescence change may be represented by curve A in fig. 76. Curve A may be taken to represent a change of this kind in all ordinary steels, no matter what amount of carbon they contain, and the shape

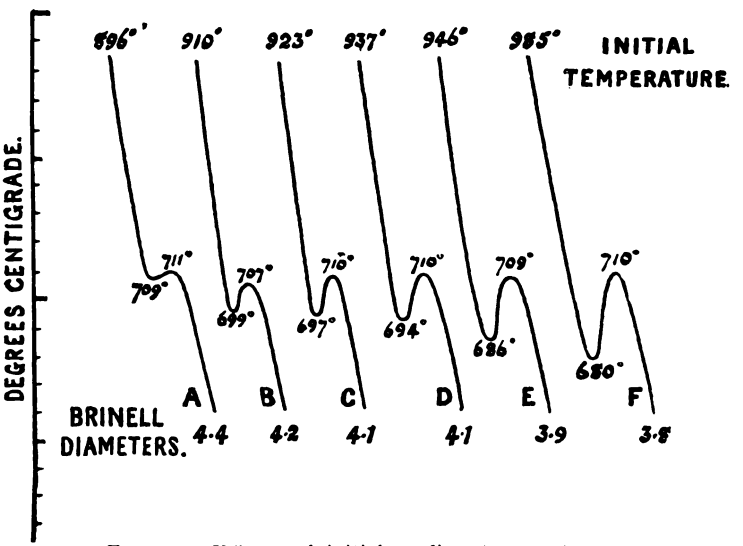

FIG. 76.—Effects of initial cooling temperature on chromium steel.

of the arrest period, or " jog," does not vary greatly however high the initial temperature may be. If the steel is quenched before the arrest is due to take place, then the formation of the pearlite laminæ is wholly or partly prevented and the steel is hardened.

If a steel contains, say, one and a half or two per cent. of chromium, curve A in fig. 76 may be taken to represent the form of arrest when the specimen is cooled from a temperature between 800° and 900° C. But if the specimen is cooled from above 900° C., the shape of the arrest point alters as in curve B, and an alteration of the same kind, but of greater intensity, occurs as the initial cooling temperature is increased,

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i.e., the critical arrest on cooling appears at lower and still lower temperatures, although when it does occur the temperature returns momentarily to the normal figure of 710° C.

This property of metals is very similar to what in liquids we call surfusion. In these days when every other person is interested in photography, an acquaintance with the phenomenon of surfusion may be assumed to be common knowledge. A sufficiently strong solution of commercial "hypo" made up with hot water deposits crystals on cooling as soon as the limiting saturation point is reached. If the water and crystals are clean, and the liquid is undisturbed on cooling, then a supersaturated solution may become cold and remain quite clear. But if for any reason one single crystal should form, then the remaining crystals of supersaturation form very readily.

If the solution containing hyposulphite crystals be heated slightly, part of the crystals will redissolve and fall out again on cooling without any sign of surfusion. If the solution be again reheated to a higher temperature, more of the crystals will dissolve and again fall out on cooling. But if on each successive occasion the temperature be increased, then on each subsequent cooling the crystals may fall out again, but the tendency to do so will be less and less, because the nuclei are less, and, finally, when the temperature is high enough to dissolve all the crystals, none of them fall out again on cooling.*

This may not be in all respects a satisfactory parallel to the behaviour of steels illustrated in fig. 76, but whilst bearing in mind the much greater freedom of movement in the liquid medium it may be pointed out that in the critical cooling range of the steel something is falling out of solution. Also the tendency to fall out becomes less as the maximum heating temperature is increased, and when high enough (about 1,100° C. or over) the steel cooled at normal rates to atmospheric temperatures does not exhibit an arrest period at all, and nothing falls out of solution ; that is to say, under these circumstances the steel remains hard just as the hyposulphite liquor remained clear.

In the progression of curves from A to F (fig. 76) the arrest temperature at which the carbides begin to fall out of solution becomes successively lower, and the steel therefore becomes more and more viscid and less favourable to

* The experiment succeeds better with sodium acetate.

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structural rearrangements of any kind. The greater tendency for free carbides to form as the temperature falls below that at which the arrest should normally occur is therefore opposed by the greater viscosity of the solid medium in which the change has to take place, and this medium becomes ultimately so rigid that the change cannot occur at all.

IRREGULARITIES OF AIR-HARDENING.

A feature exhibited by certain air-hardening nickel-chrome steels, and by some other kinds of air-hardening steels, is illustrated by fig. 77. When the material is allowed to cool in air from temperatures below 900° C., the arrest occurs, with more or less evidence of the surfusion effect at

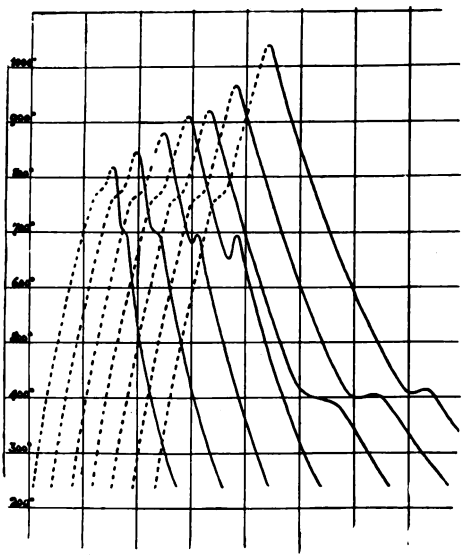

FIG. 77.—Effects of initial cooling temperatures on nickel-chrome steel.

about 700° C. When, however, the initial cooling temperature is 925° C. or over, the arrest occurs at 400° C., and again exhibits surfusion effects. But if the rate of cooling is very slow, say not more than 100° C. per hour, the arrest occurs always at 700° C.

Variations of this kind in objects made from air-hardening steel may lead to serious kinds of defects. If, for example, an object is heated in a furnace to some temperature below the furnace temperature, then its thinner parts may be hotter than 900° C. and its thicker parts less than 900° C., and on

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cooling the latter will be hardened on passing through a temperature range of about 700° C., but the former not until a temperature of about 400° C. is reached. It may by chance happen that the thinner parts will also cool so much more rapidly that they pass through 400° C. at the same time as the thicker parts pass through 700° C., but otherwise the hardening, and the changes in volume accompanying it, occur at different times with the production of stresses which may lead to disaster.

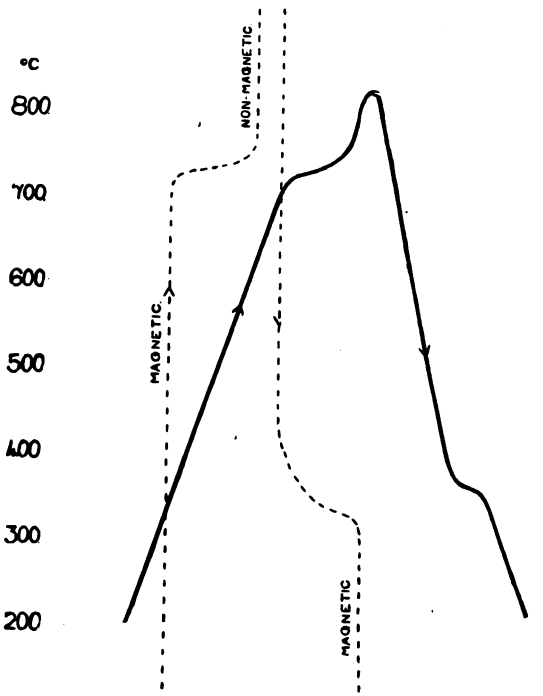

FIG. 78.—Effect of rate of cooling on thermal and magnetic changes.

Another effect of rate of cooling and variation of initial temperature which is related to the last, but much more important because it occurs in most of the steels used for air-hardening gears and other automobile parts, is illustrated by fig. 78. Starting at any temperature from which nickel-chrome steel can be intensively hardened, the arrest on cooling under normal conditions will occur at about 300° C.,

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but if the cooling is made to take place very slowly, then the arrest occurs at 650° C. Except on very prolonged cooling from an initial temperature between 750° C. and 800° C., neither the quickly cooled nor the more slowly cooled material is quite soft. But the latter is always the softer of the two, not only because less of the carbides are retained in solution, but also because whatever hardening effect has taken place is subject on the one hand to a tempering effect from 300° C. downwards, and on the other hand to a tempering effect from 650° C. downwards. The course of these changes can be followed magnetically, as suggested by the dotted lines in fig. 78.

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X.

HARDENING AND TEMPERING.

Hardening Process.

THE high carbon steel envelope around cemented objects is, to all intents and purposes, tool steel. It lacks the advantage of having been worked down to low redness, but this is not a very serious drawback if the case contains no appreciable amount of free cementite. A normal case can be refined by heating just beyond the hardening temperature, but if it contains much free cementite higher temperatures are necessary; and as the eutectoid and hyper-eutectoid parts of the case cannot be refined together, the temperature suitable for the refining of one leaves the other in a comparatively coarse state.

The author has dealt elsewhere ("The Heat Treatment of Tool Steel," Longmans, Green, and Co.) with the varying changes and conditions affecting the hardening and tempering of tool steel, and needs, therefore, to refer only to such conditions as apply equally to the heat-treatment of structural automobile steels or especially to case-hardened steels.

UNIFORM HEATING AND COOLING.

A statement of the conditions favourable to satisfactory hardening can easily be made: it is necessary only to heat the object under treatment in a uniform manner throughout and then quench it, also uniformly, at a rate which is fast enough to keep the carbides in the interdiffused or dissolved state. To perform the operations in this ideal manner is impossible, however simple the shape of the specimen may be.

When a piece of steel is heated at a uniform rate, it expands with approximate uniformity; but when the range of temperature is reached at which thermal changes occur (*e.g.*, 740° C.) the steel expands at a slower rate, or may actually contract. In whatever kind of furnace the steel may be heated, there is no possibility of this volume change taking place in every part of the object at exactly the same moment; and if parts of the object are expanding at the same time that other parts are contracting, then harmful stresses, or even distortion, must occur. With the intention

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of avoiding such defects, certain kinds of delicate tools are heated with extreme slowness, say, during six hours instead of in half an hour, so that the critical density change may occur almost simultaneously throughout the tool.

When a piece of steel is cooled at a uniform rate, it contracts with approximate uniformity; but in the range of temperature at which the critical thermal changes occur, it contracts at a slower rate, or may expand. And, just as on heating the volume changes cannot be made to occur simultaneously, so on cooling even at very slow rates the critical expansion occurs earlier in the thinner and later in the thicker parts. When the rate of cooling is accelerated so that parts of the specimen are more or less hardened, then the only precaution which can avoid cracking or a disagreeable amount of distortion lies in the shape and substance of the specimen.

The cooling of the interior of a specimen must take place entirely through the surface, and the outward form is therefore of great importance. It is also obviously the part of the specimen which first becomes rigid and least able to accommodate itself to the unavoidable changes in volume, critical and otherwise, which accompany cooling operations; hence the origin of cracks, in sound material, is mainly at the surface.

ANGLES AND CORNERS.

When two adjacent surfaces come together to form an angle or a corner, the rate of cooling about the angle or corner is greater than elsewhere, and the material in those places is, therefore, rigid earlier and less able to accommodate itself to volume changes; hence the great proportion of cracks originating at sharp angles and corners, which are avoidable by the substitution of rounded corners and fillets. From one-fourth to one-half of all the cracks occurring in hardened steel may be ascribed to avoidable sharp corners and angles, and as a very serious percentage of fractures in structural steel parts arise from a similar cause, it may be permissible to relate a few observations of an elementary kind lying within the compass of general experience.

FORMATION OF CRYSTALS.

When steel, or any other crystalline substance, is cast into a mould, the freezing (or solidifying) commences at the sides of the mould, if the steel to begin with was quite fluid. Assuming the mould to be made from cast-iron, and its cross section a square, then the freezing in any plane would occur most rapidly at each of the four corners, and the crystals

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lying in and about the corners, in consequence of the rapid cooling, would be comparatively small ones. Crystals would grow also from the sides of the mould, and as their growth sideways would be hindered by the adjacent crystals, and their growth forward into the fluid mass would be free, they would be long and narrow in shape. The crystals growing from any one side of the ingot mould, presuming the central mass remained fluid, would meet the crystals growing from the adjacent sides, and a boundary to the cooling effect of each side of the mould would be visible on a polished and

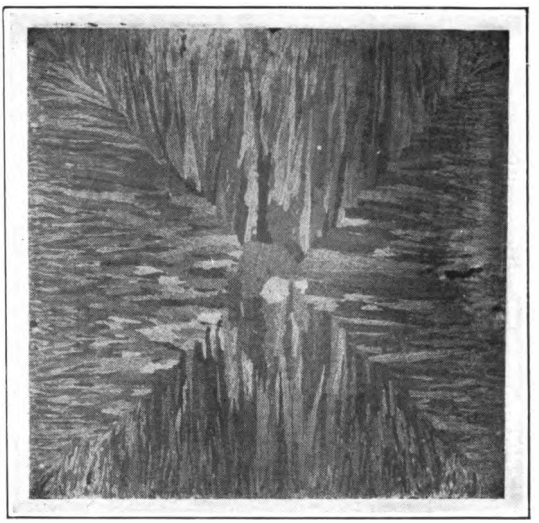

FIG. 79.—Polished and etched section of chrome steel ingot.

etched specimen, or on a fractured surface, as lines lying diagonally on the square. Fig. 79 reproduces on a reduced scale a polished and etched section made from a chrome steel ingot to illustrate the foregoing remarks.

The diagonal lines in fig. 79 are lines of extreme weakness, partly because they are the lines of contact between crystals growing in directions obliquely to each other, and partly because they are coincident with the intersection of the planes in the ingot, which at successive moments were the last to solidify. Consequently, the diagonal lines are rich in segregates and non-metallic impurities, are likely to be occupied by elongated gas cavities, and are also in the position where

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small cavities caused by shrinkage stresses would form. The influence of the segregate plus shrinkage cavity would account for a great deal of the observed weakness along the diagonal lines, and it is not possible to determine, apart from this influence, how much of the diagonal weakness is due only to the crystalline arrangement.

It has been suggested that the weakness of angles and corners in an object which has been hardened is identical with the diagonal weakness in fig. 79. Such, however, is not the case, as a hardened tool is not likely to contain favour-

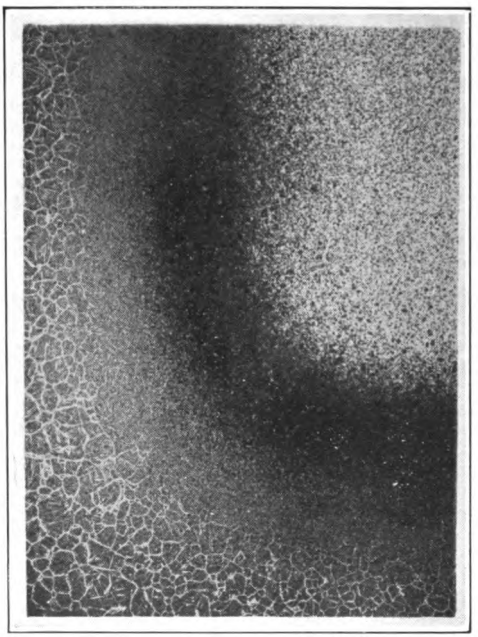

FIG. 80.—Crystal outlines about corner in quenched bar.

ably located segregates and cavities, and it does not form crystallites, elongated or otherwise, during the cooling. Whether a piece of solid steel is cooled quickly or fairly slowly does not make a great difference to either the size or the shape of the crystals of which it is composed, and it is equally indifferent whether the piece of steel has become quite hard or remained quite soft. The general truth of this remark is illustrated by the corner of a case-hardened bar

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reproduced in fig. 80. The white outlines of free cementite about the crystals enable the shapes of crystals formed about cooling surfaces from the fluid state (fig. 79), and those existing in solid metal during hardening, etc., to be compared.

SHRINKAGE.

On quenching a piece of steel its volume changes, and the effects may be compared to the effects of shrinkage in clay on drying, which have been described as follows* in relation to the drying and burning of a boy's model steel-melting furnace such as is illustrated in fig. 81.

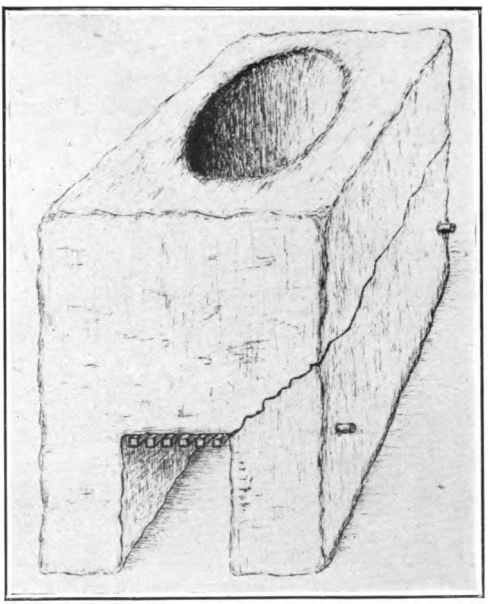

FIG. 81.—Clay model of crucible steel-making furnace.

"The first clay model you made cracked through the sharp corner of the fire grate, either during the drying or annealing (burning); and both crucibles and crucible lids would crack if coke dust or burnt clay were not added to the mixture of raw clays from which they are made; and they would, like the model, in spite of that precaution, if they were not made of uniform thickness, or with the thicker and thinner parts running gradually into one another.

* "The Art of Steel Making."

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"Clay shrinks on drying, and shrinks still further when it is made red-hot. The hotter it is made, the more it shrinks. During shrinkage the clay gets smaller in every way, just as a growing boy gets bigger in every way. If the clay model could shrink in the same gradual and uniform way as a boy grows bigger it would not crack, but one cannot wait as long as that. Dried clay is not very strong. A piece half an inch in thickness can be broken easily between the fingers. It breaks off short without bending, and, however gently it may be pulled, it does not become appreciably longer before it snaps in two.

"The pillars of the ashpit are thinner than the body of the furnace, and they therefore dry more quickly: that is to say, they get thinner at a greater rate than the body of the furnace to which they are attached. During the very slow drying in a warm place this difference in the rate of drying or shrinkage is very small; but in the annealing furnace the complete burning is done in a single night, and the thinner parts, *i.e.*, the pillars, get hot and shrink much earlier than the furnace body.

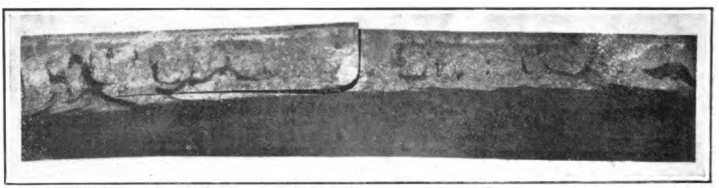

FIG. 82.—Crack between hard and soft parts of flat bar.

"Here, then, you have one part that will and the other part that will not shrink. They simply cannot help themselves: one must and the other cannot. The only possible way of keeping them together would be for each to stretch a little; many disputes and disagreeable partnerships can be managed in that way, but clay cannot. It has not got a stretch in it when dried, and the unavoidable therefore happens—the thinner and thicker portions pull apart, and the regretable crack at the top of the pillar tells us quite plainly that we have asked the clay to do what in the nature of things is impossible.

"We can help ourselves in making the next model in either of two ways. Firstly, by making the variation in thickness between the pillars and the furnace body very

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gradual; this spoils the resemblance to the original, but it is easy to see that it helps the model during the drying and annealing, both by allowing the shrinkage to take place more uniformly, and also by doing away altogether with the sharp corner about which the shrinkage strains were concentrated. Secondly, by making the pillars from separate pieces of clay. This latter is the easier and safer way. It may be adopted without inconvenience in the model, but in many other fire-clay and metal objects used in steel-making and the engineering trades it may not be adopted, and one may, therefore, see many things spoiled by cracks through angles (and about sharp corners) like the clay model, and for the same reason."

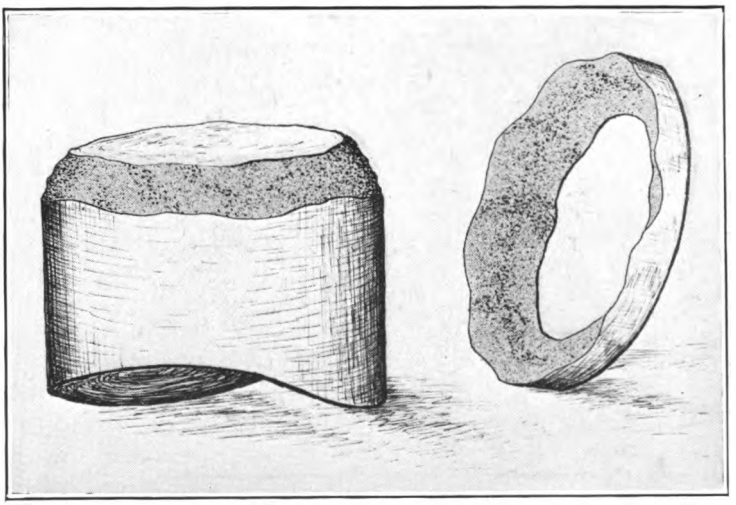

FIG. 83.—Effect of hardening stresses on sharp corners.

SHRINKAGE CRACKS.

A flat bar of steel, if heated uniformly and quenched by steady immersion of a portion only of its length, will invariably be weakened along the sharp line dividing the hardened from the unhardened portion. If the steel is very hard, it will frequently crack along the dividing line, either before or soon after taking from the water, and the crack generally starts in the middle of the flat face of the bar. This is illustrated by fig. 82, which represents a piece of file steel quenched on the top edge only. After removing from the water the hard edge was, of course, convex; but when it cracked shortly afterwards along the division between the harder and softer parts,

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it became approximately straight again. In a large section there is always some part in the interior where this condition, to some extent, prevails, and the condition is greatly emphasised where surfaces meet to form sharp corners. Along some curved surface within the bar, the completely hardened and incompletely hardened material are in contact, but whereas the former has become permanently expanded, the latter is merely stretched; and when stretched beyond the limit of its endurance it breaks, and in extreme cases, from a round bar with flat ends, the edges spring away in a complete ring, as illustrated by fig. 83. Splintering of the

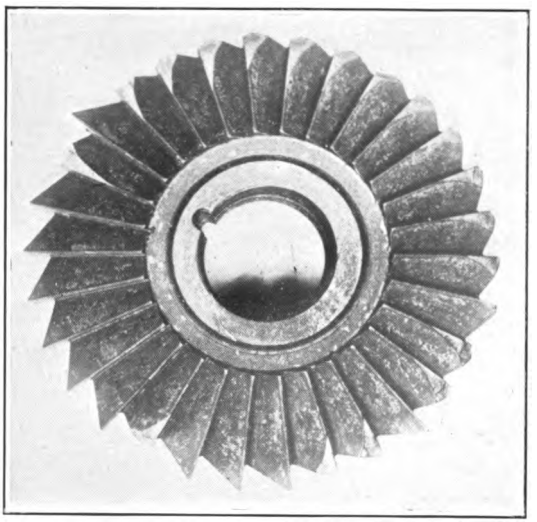

FIG. 84.—Splintered teeth of milling cutter caused by hardening.

same kind has occurred on the teeth of the cutter reproduced in fig. 84. As a crack due to rearrangement of crystals at right angles to the cooling surfaces would follow a path bisecting the sharp corner, the impression that selective crystalline structure has anything to do with this form of cracking may be dismissed.

The cracks which form about sharp angles are also in no way influenced by selective crystallisation during quenching; crystals, in fact, are not formed at all during quenching, and the direction of the crack through the sharp angle being the same as it would be if the crystals were selectively

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arranged is a mere coincidence. The cracks through angles, like those about corners, are due to straining caused by the unequal expansion of the hardened material adjacent to the angle; and they are particularly easy to form because the apex of the angle is sharp and too small to stretch at all without breaking.

If a ring of steel, as represented in fig. 85, were hardened, its exterior diameter would be increased, and so also would its circumference. The hardening effect would be greater in the darker parts, and the natural result would be a tendency to pull open the square-cornered gap, which tendency could

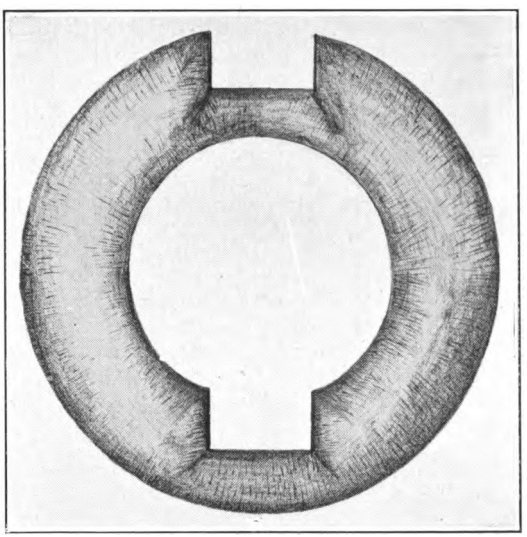

FIG. 85.—Sharp corners in steel disc.

be resisted without cracking only if the apex of the square angle on which the stress would be localised were able to stretch sufficiently to equalise the increased circumference of the ring; and this, the apex being glass hard, it could not do. Similar reasoning would apply if the gap, like a keyway, were on the inside, and the internal diameter, as sometimes happens, were to contract, except that the gap would be acted upon by compressing instead of extending forces.

COMPRESSION CRACKS.

It is not generally realised that cracks are very apt to arise at the point of maximum compression; and bend test pieces, which on examination are reported to be perfectly

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sound, have frequently a small crack on the inside of the bend. This is illustrated by the photograph of a sectioned bender in fig. 86; the same figure shows on the lower part of the fractured surface of a square bender the lamination due to compression.

When a hardened object is perfectly symmetrical, the stresses induced by quenching may be so well balanced that it becomes difficult to cause fracture. A steel ball, for example, may be hardened a number of times, and if correctly hardened it is not likely to break; but a small flat surface filed on it will start a crack on the first or second quenching. Also, if a small part of the surface be left soft, or if for some reason a number of minute points on the ball are imperfectly hardened, then fracture in use is more likely to occur than otherwise. This, amongst other causes, accounts for the pitting and chipping sometimes observable on used balls.

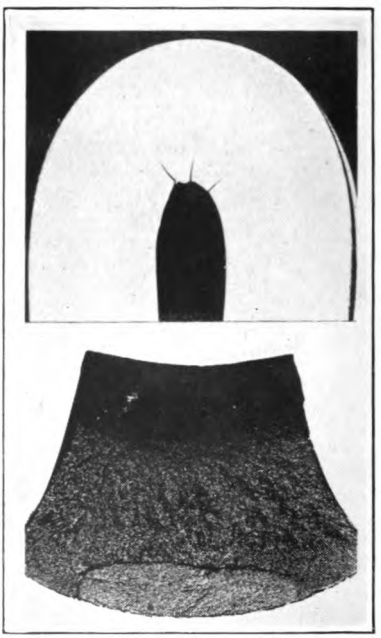

FIG. 86.—Cracks and fracture due to compression.

STEEL BALLS.

It would appear at first sight that a steel ball was one of the easiest possible objects to harden satisfactorily. But that is not so, and on balls, as well as on semi-spherical ends of other objects, a skin softness may occur, due to imperfect quenching, and not at all related to decarburisation, which is not always entirely avoidable.

If a piece of heated steel were dipped into water and immediately withdrawn, and then again plunged and allowed to remain till cold, the steel would be soft on the outer skin, but quite hard beneath it, because the first dipping hardens a thin envelope of the material, which is then softened by the heat in the mass, but not raised again to the hardening temperature before the second immersion. Now, when a ball is

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dropped vertically into a tank of water, it carries with it to some distance below the surface rather more than its own volume of air, and for a short time after entering the water only the under side of the ball is in actual contact with it, the water being kept off it elsewhere by the attached bag of liquid skin, as shown by the instantaneous photograph A in fig. 87.* As the ball sinks in the water, the ring of liquid, moulded by the elastic force at its surface (B in fig. 87), breaks, scatters moisture on to the hot surface of the steel, and depresses the temperature of the parts where it falls before they are surrounded by a sufficient volume of water to cool them continuously. The heat of the ball generates steam immediately, and breaks or distorts the elastic bag of liquid in unpredictable ways, but the final result, as one might expect, is the occurrence of soft patches, and sometimes the occurrence of very small circular specks which cannot be detected by the file, but which are developed by the etching test (page 42), and resemble in appearance the brown specks on a sparrow's egg. If balls of this kind were allowed to pass into service they would be apt to spall and crack; but balls are hardened commercially from an automatic machine and given a spinning motion just before they are quenched.

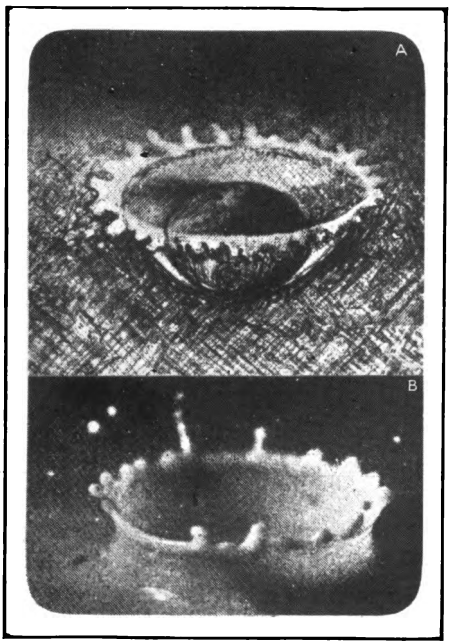

FIG. 87.—Effect of surface tension of water on immersed ball.

The double-quenching operation, largely used in the production of fibrous cores in case-hardened objects, which has been fully discussed on page 19, cannot be satisfactorily

* Reproduced from Professor Worthington's book on "The Splash of a Drop."

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applied to objects whose shape is intricate or otherwise dangerous from the hardener's point of view. Only the simpler shapes can withstand a drastic quenching from a high temperature, followed by a second hardening, without either cracking or visibly distorting. To a certain extent distortion always occurs, and whether the increase of it by double-quenching, and the consequent disturbance of the hard outer envelope, is fully compensated by a fibrous cone, is at least questionable. The question cannot be settled by counting the number of pieces which crack or are otherwise rejected in the hardening shop.

DISTORTION

The constituents of steel in the hardened state are not the same as those in the annealed state. If they are relatively greater or less in volume, *i.e.*, in specific gravity, then a volume change must occur on quenching, and this change would be predictable if we knew the properties of the new constituents, and in what proportions they were present in the quenched steel. But, apart from mere change of volume, a change of shape is always brought about by the unequal rate at which the parts of an object are quenched, and this change, though slight, applies to the softest as well as to the hardest steels.

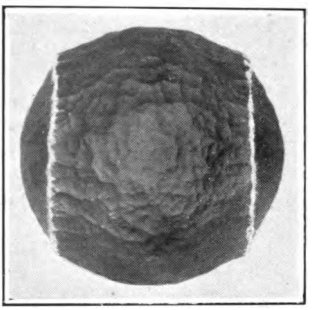

FIG. 88.—Disc of mild steel distorted by repeated quenching.

When a disc sawn from a round bar is heated, it gradually expands in all directions, and on very slow cooling it contracts again to its original shape. This operation might be repeated one hundred times or more without any visible alteration in its shape. But if the hot disc be plunged into water, or otherwise cooled quickly, the first parts to contract and harden are the edges, and these compress the material which is still hot, and distend it in those directions which offer least resistance. After repeating this operation a sufficient number of times, the disc either sheds its edges, if made from hard steel, or loses its shape, with or without cracking, if made from soft steel. The disc will bulge first on the flat sides and then on the periphery, until ultimately its shape, as seen in fig. 88, becomes approximately that of a sphere. In the same way, a cube of mild steel would also

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tend to become spherical, and it is for a similar reason that tongs used in reheating furnaces, which are alternately heated and quenched, lose their shape and crack. The distortion which can be made visible to the naked eye by repeated heating and quenching occurs also, but to a lesser extent, on quenching once only, and this fact should never be overlooked by engineers in designing tools or structural parts which require to be hardened.

Tempering Process.

The structural changes which occur on tempering a piece of hardened steel cannot be followed by means of the microscope with any degree of certainty, and no good purpose would be served by adding to these pages a number of photographs which, taken by themselves, are not very convincing to the practised microscopist, and are merely bewildering to the craftsman with a taste for applied science. When a small piece of mild steel, quenched rapidly from above the temperature at which complete inter-diffusion of its constituents takes place, is reheated to any temperature below 600° C., its microscopic structure is hardly distinguishable from that of the quenched piece. A difference is distinguishable in the rate at which it is attacked by the etching reagent, and also by the dark and loosely adherent film which forms on its surface; but, apart from such incidentals, neither the microcsope nor microscopic methods have any assistance to offer which is of workshop value.

The varied effects of reheating hardened steel are determined most easily by mechanical methods, and of these the Brinell hardness test serves a more widely-useful purpose than all the rest put together. In fact, the Brinell test, confirmed occasionally by the results of impact testing, will enable the heat-treatment of structural steels to be closely followed and efficiently controlled. The impact test is desirable, also, because in nickel-chrome alloy steels the same Brinell figure may be obtained by heating above or below a certain range of temperature (about 650° C.: see fig. 74), but not the same impact figure. Moreover, the correct impact figure taken with the desired hardness, as controlled by the ball impression, ensures the desired mechanical properties.

Case-hardened articles are very rarely tempered after quenching. The following quotation presents the prevailing view: "It will be realised that, since the chief purpose of

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tempering is to toughen hardened steel, and since case-hardened articles depend for their toughness on the toughness of their cores. little is to be gained by tempering them." This view, however, ought not to be adopted without further consideration.

TENSILE TESTS.

The results of tensile tests recently made by various observers on hardened and tempered tool steels show, it is claimed, that tempering up to 200° or 300° C. actually increases the hardness of the steel. This statement is not confirmed by the usual workshop tests; and, whilst it may be admitted that a test piece will stand a greater tensile load after tempering, this cannot be accepted as proof that the hardness of the material is greater under the usual conditions of wear. It may, in fact, be ascribable to the difficulty of preparing and adjusting test pieces from hardened steel to lie mathematically parallel to the direction in which the pull is exerted, as either the slightest bend in the test piece or the slightest defect on its surface would cause premature fracture, whereas either of these slight defects might be practically negligible in the use to which a case-hardened article is applied. In this instance, as in many others, the results of the ordinary tensile test should be cautiously interpreted

LOSS OF HARDNESS.

The Brinell test, or a sclerometer test (which measures the dimensions of a scratch made with a loaded diamond), is a more reliable means of measuring the softening effect produced by tempering hardened steel. The former method was used by Maurer, and the latter by Heyn and Bauer, both of whom used a tool steel containing about .90 per cent. carbon. Their separate results were:

Tempering Temperature.	Percentage Loss of Hardness induced by Quenching.	
	Maurer.	Heyn and Bauer.
100	0	2.5
200	13.0	14.0
300	38.0	41.0
400	68.0	70.6
500	94.0	87.5
600	100.0	95.7

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If, then, we are guided by these figures, as an approximate representation of the softening effect of tempering, and by the general result of workshop experience with hardened and tempered cutting tools, we are led to conclude that the tempering of case-hardened articles, for some purposes at any rate, may be advantageous. A series of bending tests on case-hardened bars shows an improvement both in strength and toughness after tempering at 200° C., *i.e.*, at a temperature just below that at which the case ceases to be file hard. If the conditions of service permit it, a higher reheating temperature than 200° C. may be advantageously used, as the increased toughness of the cemented casing is thus reinforced by the soft core in ways which are not possible when the core is surrounded by an envelope of material that cannot yield without cracking.

Hardening and Tempering Plant.

Owing to lack of inside experience, the author is not able to discuss the relative merits of large furnaces designed for carrying out the cementing operation on an industrial scale. But the smaller furnaces used for refining the core, and the final quenching, together with the accessories of these important operations, may be briefly considered.

WORKING FURNACES

The most important feature of a hardening furnace is that the temperature of the used part of it shall be uniform, as it is not otherwise possible to quench from a uniform temperature, which, generally speaking, is of more consequence than a variation of a few degrees from a chosen temperature. For exact work it is desirable to have a pressure governor on the gas supply; and to facilitate the fixing of any particular temperature, or the required variations in temperature, the use of quadrant gas taps with arm and pointer may be recommended. Both these accessories are favourable to accurate working; they also save gas, which in this case is good economy, although economy in gas consumption, taken by itself, is but poor compensation for want of accuracy and facility of working.

But the operator has no right to expect that makers of gas or oil furnaces can supply plant which is fool-proof. Hardening requires the exercise of skill, and no assistance in fixing the stopcock at the correct angle or controlling the gas pressure will avert wasters if the dampers are neglected and the methods of charging the furnace are left to take care of themselves. The man who best understands how to

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work a furnace is the workman who realises that the furnace works him, and he must respond and act according to circumstances. This remark applies to all kinds of furnaces, whether for hardening, reheating, or melting purposes, and the meaning of it will be appreciated by those who are themselves, and those who have in their employ, really skilful furnacemen.

As it is not usually necessary to protect the work from the products of gaseous combustion, it is better to use trays and slabs instead of muffles. Muffles are easily broken and expensive to replace ; they are also wasteful and more likely, unless unreasonable precautions are taken, to promote scaling and irregular heating than to avoid it. There is also less variation in temperature between the bottom of the furnace and the gaseous atmosphere above it when trays are used. The bottom of a gas-fired hardening furnace is nearly always either hotter or colder than the rest of the furnace, and it is not advisable to lay any delicate piece of work directly on to the furnace bottom, even if it can be occasionally turned over, because want of uniformity in the rate of heating, as well as in the final temperature (see page 137), can cause distortion. The work should be placed on racks or pegs made from bent steel or cast iron, so that it becomes evenly heated in every part.

The author favours the use of salt bath furnaces for reheating small articles prior to quenching, and also the use of low melting point salt bath furnaces for tempering at temperatures of 250° C. and over ; and has shown elsewhere how they can be advantageously used within narrow margins of temperature with the very simplest forms of pyrometric control. The subject of industrial pyrometers has been discussed in the same place,* but the following remarks may be added :

PYROMETERS.

A pyrometer is designed to indicate the temperature of that part of a furnace at which the hot junction, or the acting end of it, lies ; but it gives no guarantee that the work placed in the furnace will be uniformly heated, nor that the furnace itself even has a uniform temperature in all its parts. As a matter of fact, no furnace in use ever is at a uniform temperature throughout, with the possible exception of a salt bath furnace, which is kept in constant motion. Every kind of pyrometer, therefore, is abused unless it is used with

* "The Heat Treatment of Tool Steel," page 91 (Longmans).

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due regard to its limitations; and automatic temperature records which are used to make an improbable story sound plausible are more of a hindrance than a help. In short, pyrometers indicate temperatures; they do not control them, and though an invaluable adjunct to intelligent judgment, they are not a substitute for it.

A very reasonable objection to the earlier forms of thermo-couples and indicators was that they were too delicate to be put into the hands of workmen. This objection has less force nowadays, partly because the value of heat treatment operations is widely realised and the operations are entrusted to better paid and more capable men, and partly because the instruments have been made more suitable for works purposes. But it is not to be expected that pyrometric apparatus, however simple, will be indifferent to careless handling, and it must be admitted that the robustness of many modern instruments is obtained at the expense of accuracy.

The base metal couple, which is cheaper and possesses higher thermal constants than couples made from platinum metals, has found many users who are satisfied with its behaviour; it may therefore be said to justify its existence and offer encouragement to those who are engaged in its manufacture and development. But if an outfit is going to be used carefully, and a good deal depends on its indications being consistently reliable, then the slightly increased cost, apart from the first cost, of using platinum rhodium couples is a good investment.

PROTECTION FOR COUPLES.

The protecting tubes for platinum metal couples used formerly to be made of porcelain, which was fragile in itself and sensitive to sudden changes of temperature; it was therefore costly. To use an iron sheath only is risky, as iron, and particularly wrought iron, tubing is not impervious to hot gases, and furnace gas soon makes platinum wire brittle. The use of an iron sheath over an inner tube of porcelain or fused silica appears to be an ideal protection for platinum couples, but the protected couple bears a certain resemblance to a poker, is sometimes spoken of as a poker, and is apt to be used as such. In any case, the iron tube may sag, and in doing so, or during the subsequent effort to straighten it, the inner tube gets broken, without any responsible person being the wiser, and the couple continues in use saddled with the expense of an inner tube from which it gets little or no benefit.

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Having had experience with most forms of thermo-couples and methods of protecting the expensive wires, the author recommends the use of a single tube made from thick-walled silica tubing. Such a protecting tube is certainly fragile, it looks fragile, and everybody knows it; it therefore gets treated accordingly. But if the diameter of the tube is, say, one to one and a quarter inches, its average life when in daily use in a hardening furnace, accidents excepted, will not be far short of six months, and when once it gets broken there is no overlooking the fact, and no danger, therefore, of the expensive couple wire itself being exposed, in an unprotected state, to the deteriorating influence of furnace gases. Paradoxical as it may seem, the cost of maintaining over one hundred platinum metal couples in use has decreased by nearly one-half since protection (!) by an outer iron sheath was discarded, the couples in question varying in length from three to twelve feet, and the range of temperatures to be measured being generally up to 1,000° C., but in a few cases up to 1,200° C.

TEMPERATURE INDICATORS.

The choice of a temperature indicator is equally as perplexing as the choice of couple wires. If a single instrument only is required, then any good millivoltmeter by a well-known maker, which is graduated in degrees C. or F. to suit the thermal constants of the couple wire, will serve. But if a considerable number of indicators and recorders are likely to be required, it is a great convenience to have them interchangeable in all respects. The favourite form of indicator is a pivoted coil instrument, and until recently these were made with an internal resistance not greater than 200 ohms, and generally between 90 and 120 ohms. But some indicators and most recorders are suspended coil instruments, which can, without difficulty, be made with an internal resistance up to 600 ohms, and are generally made with a resistance between 300 and 450 ohms. The readings on a recorder installed in the manager's office and those on the indicator in use at the furnace will not be in agreement unless both instruments have the same internal resistance; and though in any single instance it would not be difficult to make the necessary adjustment, it would be impracticable to provide beforehand for variations arising from the use of couples differing in length; and it would certainly interfere with the laudable desire to make all instruments and couples interchangeable.

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TEMPERATURE RECORDERS.

There are many reasons why at least one automatic temperature recorder should be installed in every works which is seriously employing heat treatment processes. If that one is wisely used, others are likely to be added to it. With this probability in mind, the author would recommend that the indicator intended for the use of the furnaceman should be of the suspended coil type, with internal resistance of the same order as that of the recorder—say, 450 ohms. If it is intended to carry the indicator from place to place, then a pivoted coil instrument is preferable, but not otherwise. The couples can be made, repaired, and calibrated on the

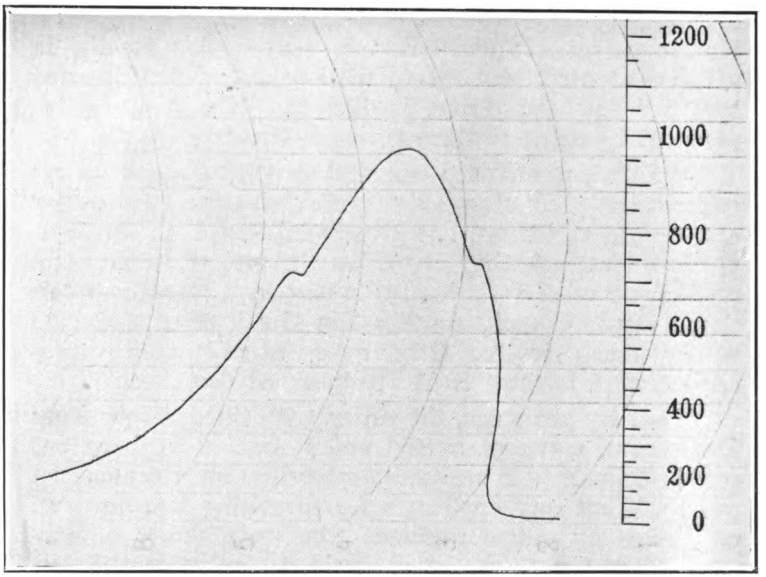

FIG. 89.—Heating and cooling curve made on works recorder.

spot, and this is highly desirable when half a dozen couples or less are in use, though a capable man would be able to repair and keep fifty of them in order; in this work a recorder would be found useful.

Under suitable conditions the phenomenon of recalescence is visible to the naked eye, and its observance can be made of direct use in hardening certain kinds of tools. But to trace its occurrence during the rise and fall of temperature is interesting, and also useful, to the intelligent hardener. These observations can be made with surprising ease by

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means of an automatic temperature recorder; in fact, a couple in imperfect contact with a large mass of work in the furnace will frequently show the critical change point on the record as the furnace is being heated. But if a heating and cooling curve is being made intentionally, the specimen under observation should have a hole bored to the centre of it in which the couple can be inserted. The specimen may weigh as much as twenty or thirty pounds, and be heated in an ordinary gas-fired furnace using a tray instead of a muffle, in which case a hole one half inch in diameter will receive the couple, protected by a thin sheath of fused silica; or it may weigh not more than one ounce, and be conveniently heated in a small vertical electric furnace, or even over a blast lamp, suitably aided by a non-conducting mantle, in which case the insulated but otherwise naked couple is inserted into a hole about 3 mm. in diameter. The kind of curve produced by either of these means is illustrated by fig. 89.

As a piece of ordinary tool steel containing about .90 per cent. carbon gives always clearly marked arrests on heating and cooling which are not greatly influenced, in the temperature at which they occur, by the rate of heating and cooling and other variations, it is obviously possible by this simple means to make a calibration of a number of couples without much trouble. Other means of calibrating couples are described in the "Heat Treatment of Tool Steel."

SENTINELS. About ten years ago, the writer, with three or four other Englishmen, was sent abroad and instructed to carry out certain delicate heat treatment operations on a commercial scale, without any appliances for measuring temperatures, and aided by native workmen who were almost entirely ignorant of the properties of steel. In order, in the first instance, to plot variations of temperature in the furnaces, use was made of the melting point of such substances—metals, metallic alloys, and salts of metals—as were available. Use was finally made of three or four metallic salts which appeared to have well-marked melting points corresponding approximately with temperatures at which the desired changes in the steels could be brought about. One of these substances was found to melt at a temperature just below that at which the steel would harden, and another at a temperature higher, but not much higher, than that at which the steel would harden. These salt substances, cast into small cylinders and covered with coloured wax to protect

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them from moisture, were used for a year or two, and carried about by workmen in charge of the furnaces with the same idea as a mechanic carries a two-foot rule. It was some time later before an opportunity occurred of determining the melting points of the salt cylinders in degrees Centigrade, and since then the small cylinders, which were a temporary convenience, have been extended in their range of usefulness and put on the market as Sentinels.*

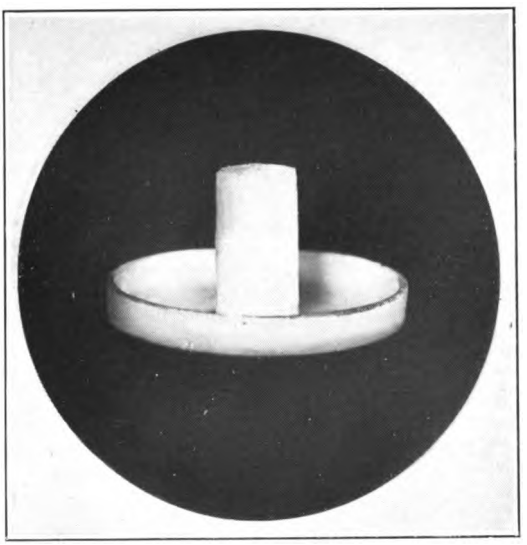

FIG. 90.—Sentinel and saucer.

The Sentinel pyrometer is a small cylinder measuring about 20 mm. × 12 mm., made from salt mixtures of definite melting points. If one of these cylinders, having a melting point of, say, 770° C., be allowed to rest on a small porcelain saucer (fig. 90) in any heated area, it will retain its shape as long as the temperature does not exceed 770° C., but when that temperature is exceeded the Sentinel melts and remains fluid in the saucer. If, however, the temperature falls again below 770° C., the fluid material sets, but will continue to pass from the liquid to the solid state, and *vice versa*, as often as the temperature falls below or rises above 770° C.

* Sentinels, fixed melting point salts for calibrating thermo-couples, etc., are manufactured by the Amalgams Co., Sheffield.

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If now a second Sentinel, having a melting point of 800° C., is placed in the same area, and the former melts and remains fluid, whereas the latter remains erect and solid, then, obviously, the temperature lies between these two extremes, and in this simple way the heat of a suitably fired furnace can be measured and maintained with any reasonable degree of accuracy.

When ground to a fine powder and mixed with vaseline, the Sentinel can be used as a paste for streaking on to objects which are being heated to a desired temperature in a makeshift furnace or a smith's hearth. But they can be used also for purposes that are not served conveniently by any other means, as, for example—

(1.) In the inside of a case-hardening box.

(2.) To exhibit variations of temperature in the same furnace.

(3.) To place inside hollow objects which need to be heated throughout to the furnace temperature.

(4.) In automatic hardening machines.

In the latter case they are placed in a hole drilled into a large steel ball; the hole is closed with a plug of asbestos or clay, and the ball, after travelling through the machine, is caught at the back end before falling into the quenching tank. It thus accompanies the work in its passage through the machine, and on removing the stopper from the hole, the condition of the Sentinel indicates clearly whether the thermo-couple, fixed some distance from the work, is indicating the actual hardening temperature; generally, the pyrometer indications are from 30° to 40° C. lower than the maximum hardening temperature.

QUENCHING FLUIDS.

The object of quenching is to keep the dissolved carbide in solution, and the more rapid the cooling, the more completely is this object attained; also, the more rapid the rate of cooling, the more excellent are the mechanical properties, for structural purposes, which can be induced in the material by reheating. The best of all quenching media is water, and the only limitations to its use are the fear of warping and cracks. Cracks arise more readily from surface defects and about sharp angles and corners on water quenching than on oil quenching, because the rate of cooling in different parts of the work is, in the former case, subject to greater variation; but many large drop stampings and forgings made from mild steel may be fearlessly water quenched, and will

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be oftener water quenched in future than in the past. Still, oil or some substitute which cools at moderate rates will always be essential for awkward shapes like crank axles.

There is no special virtue in whale oil or rape oil or in any other kind of oil apart from its flash point, which is incidental, and the rate at which it will quench heated steel. It is possible, therefore, to fill the tanks with oil which is bought for the actual service it can render, and not on account of a label or a source or origin which adds considerably to its price. The comparative value of oil for hardening purposes may be determined by observing or recording pyrometrically the rate at which a large block of steel can be cooled by immersing it in a given volume of the respective hardening fluids. For this purpose the author uses a round bar of steel four inches in diameter, on to which a long neck has been turned. A hole is drilled longitudinally to the centre just large enough to admit the fireclay insulating tubes of a thermo-couple, and the neck is extended into a handle by screwing on to it a length of wrought iron tubing. The block of steel is heated in a small furnace, through the door of which the tube projects, to a temperature of 850° C., which is registered by the furnace couple and also by the naked (but insulated) couple that has been passed down the tube to the bottom of the hole in the steel block.

The heated block, on removing from the furnace, is immersed in a circular tank containing four gallons of the hardening fluid. The block should rest undisturbed on a grid two or three inches from the bottom of the tank, and the length of the tank should permit the oil to cover the thicker part of the immersed block by a depth of three or four inches. The tank should also stand in a wooden box, and be packed all round and underneath with dry sand, infusorial earth, slag wool, or some other non-conducting and incombustible substance.

The heated block is allowed to rest quietly on the grid, and the tank may have a wooden cover. From this stage onwards the operator watches the temperature indicator and takes such observations as will enable a quenching curve to be plotted; or, more instructively, arranges for the cooling curve to be traced out by an automatic temperature recorder.

From the observed temperature of the oil before and after the heated block has been cooled in it, and from the known weight of the block and the oil, the approximate specific heat of the

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oil can be calculated. But its effectiveness as a quenching medium is determined from the steepness of the quenching curve, and may be confirmed by sawing through the block just below the end of the central hole and making a series of Brinell hardness tests across the diameter of the end face. The results thus obtained are comparative only, but so also is the question asked, viz., whether the new or cheaper oil is a reliable substitute for the oil previously used. The flash point of the oil and its tendency to thicken are considerations which can be dealt with by ordinary laboratory methods.

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XI.

SURFACE HARDENING WITHOUT CEMENTATION.

In order to confer hardness on heated steel, it is not essential that it should be immersed in a cooling fluid, but only that it should be cooled by any means whatsoever at a rate sufficiently great to suppress the physical changes which induce softness. That is to say, the hot steel has the constitution and structure associated with the property of hardness, and sudden cooling makes it permanent, whereas slow cooling enables the constitution and structure to change to a form which is associated with the property of softness.

Press hardening.

If, therefore, the braked wheel of a railway coach, in sliding along the rails, becomes red hot at the point of contact before the train is brought to a standstill, the hot point of contact between the cold rail and the mass of the tyre will cool very quickly, and be hardened in all respects as though it had been quenched. In the same way, wire haulage ropes in mines may move so rapidly over a stiff pulley that a strand or two become incandescent at the point of contact, and being instantly cooled by the mass of material, such strands become quite hard on the surface, and crack when called upon to bend. Thin objects like safety razor blades and fine saws are frequently hardened in an identical manner by being pressed between blocks of cold metal.

When a block of steel has been momentarily heated over a restricted area by the oxy-acetylene blowpipe (or electrically), the mass of metal quickly depresses the temperature and leaves the part more or less hard. It is for this reason, amongst others, that steel castings on whose surface small blemishes have been repaired by blowpipe welding, and plates which have been cut or joined together by the blowpipe, should be subsequently annealed.

Owing to its high temperature, the heating effect of a blowpipe flame is confined to small areas, in spite of the high heat conductivity of metals. But although the rate of heating is much greater than that attained by ordinary methods of heat treatment, the thermal transformations take place in the same order and in about the

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same range of temperature. The edge of a plate which has been cut by an oxy-acetylene blowpipe flame furnishes a very good example of the changes brought about by the sudden heating and cooling.

FLAME CUTTING.

The effect is most marked on the cut surface itself, but for some distance beneath the surface, as much as a quarter of an inch on a thick plate, the structural transformations due to the advancing temperature, and fixed more or less by the rapid cooling, are clearly marked. There is first the clear martensitic structure of hardened steel, then a layer of troostite which has been made hot enough but not cooled fast enough to become quite hard, then troostite patches which indicate that the temperature has not been sufficient to induce complete inter-diffusion between the transformed pearlite and the ferrite patches, and lastly, the unaltered steel divided from the rest by a fairly sharp line. This series of transformations clearly written in the steel during the fraction of a minute are all visible in fig. 91.

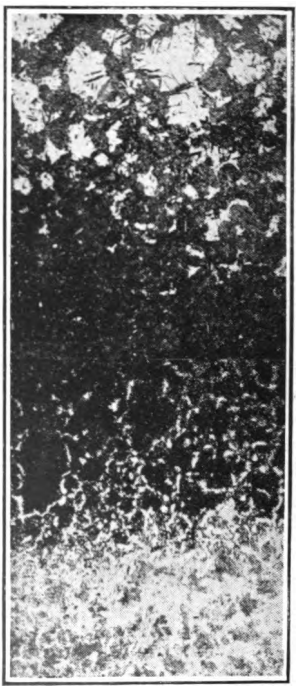

FIG. 91.

Whatever the commercial advantages of acetylene cutting may be, it is easy, from fig. 91, to realise that there are consequential disadvantages. On thin sheets of mild steel the heat is less localised and the effects are not very marked; but on thicker sheets or forgings the hard edges are a menace to subsequent machining operations, and may cause minute cracks to form, and grow later to visible dimensions. It is a consequence of the same kind which limits the use of the toothless saw for cutting bar steel into standard lengths, *i.e.*, the frictional heat melts the metal in contact with the revolving disc and leaves the parted surfaces hard.

BLOWPIPE HARDENING.

Attempts have been made to take advantage of this local hardening (or softening) arising from rapid heating by means of an electric arc or the acetylene blowpipe. A method has

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been developed by Vickers, Limited, which is said to be especially applicable to the hardening of relatively small surfaces on large articles, or where distortions are likely to be set up by the usual methods of heating and quenching. The only special equipment required is that usually supplied for oxy-acetylene welding purposes. The work to be hardened is supported in a water tank with adjustable overflow, so that whilst a portion of the surface is being heated to the required temperature the remainder of the object is kept cool.

The burner is held so that the outer portion of the flame flows in the direction along which the burner is travelling, and the heated portions of the steel should be cooled—when intense hardness is required—by arranging that the cooling water follows as closely as possible the travelling burner. A very hot flame should be used. This is obtained by adjusting the flame as for welding, and then increasing the oxygen pressure so that the flame changes in colour and appearance from a white cone to a bluish-streaked tongue when observed through smoked glasses.

Rapid heating is essential to success. In the case of a gear wheel, each tooth is not heated as a whole and then quenched, but the surface is traversed by the flame as with a paint brush. The surface is instantly raised to the hardening temperature, and almost instantly cooled when the flame leaves it. To obtain a thin but intensely hard surface, the part to be hardened should be just below the surface of the water, so that the impinging flame will blow the water film away. The normal depth of hard face is about one-sixteenth of an inch, but a greater depth can be obtained by prolonging the heat and giving the flame a wavy or rotary motion to avoid local overheating.

The patent specification (Vickers and Sumpter, 5588/1910) claims that the entire surface of an article may be hardened by traversing it with the hot blowpipe flame in the manner described. This appears to be an over-statement. One face of a tooth on a small gear can be heated by a single stroke of the flame, but when it is necessary to heat a surface in strips by moving the flame backwards and forwards and in steps, then each movement taken to harden the next step causes part of the material in the position last occupied by the flame to be tempered. By moving the flame *seriatim* over a large surface, the production of alternating bands or patches of hardened and hardened and tempered steel is therefore

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unavoidable. Such a surface, if polished and etched, exhibits alternate dark and light bands, like those seen on a smaller scale in fig. 37. It is, of course, always possible to form a single hardened strip along the pitch line of a large tooth, with the object of increasing its wear, in gears which are not generally hardened at all.

TAPER-HEATING.

It is possible to produce a hardened surface and a tough core by combining rapid heating with the method of quenching known as " broken hardening," which consists in quenching the specimen in water until the red colour has disappeared from the surface and then allowing it to stand quietly in oil until cold. The heat remaining in the centre gradually penetrates outwards into the oil, but the outer surface cannot again become hotter than the oil in immediate contact with it. The success of the method depends on heating the articles so rapidly in a very hot furnace that the surfaces exceed the hardening temperature before the cores reach it. If this ideal could be easily realised, it would be necessary to quench only in water in order to produce from previously hardened or hardened and tempered steel a really excellent case-hardened object. The process is most likely to be successful with toothed articles, but its limitations are obvious, and the partial quenching in water followed by cooling in oil is only a precautionary measure. Ordinary open hearth carbon steels are most easily handled in this way. The method is not in regular commercial use, but it is practicable for certain simple shapes, and produces objects which are much stronger than those made from case-hardened mild steel and less brittle than those made by quenching harder steels in the usual manner. The steels most suitable for this kind of treatment should contain .75 to .90 per cent. carbon. Objects comparable in size with a 1in. round bar are ready for quenching after being exposed for about four minutes in a furnace at 1,000° C.

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INDEX.

Abbot, R. R., on carburising material, 92
Aeroplane parts, Steel for, 125
Air-cooling, Effect on fibre of, 26
Air-hardening steel, 72, 75, 129, 131
Alkaline carbonates, 90
Alloy steels, 122
Aluminium, Effect of, 69
Amalgams Co., 157
Analysis of case, 62
,, gases, 84
Angles, 138
Anthracite coal, Carburising with, 82
Armour plates, 7, 38, 93
Austenite, 73
Automobile steels, 75, 116
Axles, Creeping cracks in, 110

Balls, Hardening of, 146
,, Streaks in, 40
Ball races, Requirements of, 25
,, ,, Slag streaks in, 40
,, ,, Soft places in, 49
,, ,, Testing, 96
,, Test, Brinell, 97
Bar steel, Hardness of, 101
,, ,, Toughness of, 102
Barium carbonate in carburising reagents, 54, 83, 90
Barrett, G., Method of hardness testing, 96
Base metal couples, Use of, 153
Bauer and Heyn on tempering, 150
Bending tests, 151
Beriot and Portevin on diffusion, 38
Bessemer steel for files, 1
"Blackheart" malleable castings, Graphite in, 82
Blisters, Phosphide, 91
Blowpipe hardening, 162
Bone charcoal, Conductivity of, 55
,, ,, Hydrocarbonated, 87
,, ,, Phosphorus in, 91
,, raw, Conductivity of, 55
,, ,, in carburising mixtures, 89
Boron steels, 131
Bourg and Nead on conductivity of mixtures, 55
Boxes, Case-hardening, 52
,, Discrepancies caused by, 88
Brine in hardening paste, 1
Brinell ball test, 97
,, Hardness numeral, 99
,, Machine, Description of, 100
,, ,, Utility of, 23, 71, 124, 149
Brittleness caused by overheating, 7
,, ,, phosphorus, 91
Broken hardening, 164
Bushes, Steel for, 66, 70

Calcium phosphate in charred bone, 91
,, saccharate, Conductivity of, 55
Calescence point, 9, 77, 138 155
Calibrating pyrometers, 156
Cam rolls, Grinding cracks in, 50
Camshafts, Material for, 28
Carbide of iron, 3, 6, 34, 58, 60, 78
Carbon, Carburising with solid, 81
,, steels, Mechanical properties of, 126, 130
Carbon steels, Use of, 70, 126
Carburising operation, 51
,, reagents, 77
Caron on cementing operation, 80
Caron's mixture, 54
Carpenter, Prof., on cast-iron, 52
Case, Refining of, 35
,, Strength of, 111
Case-hardening steels, 66
Casing, Brittle, 7
,, Defects in, 34
Casting, Refining of mild steel, 7
,, Repairing blemishes in, 161
,, temperature, Effect of, 117
Cast iron boxes, 52
,, steel, Crucible, 3
Cementite, 3, 6, 34, 58, 60, 78
Chain drives, Material for, 70
Charpy impact machine, 103
,, on deposition of amorphous carbon, 91
Charpy on super-carburisation, 81
Chemical composition, 116
Chromium, Effect of, 69
,, steels, 25, 71, 128, 130
Chrome-nickel steels, 29, 75, 122, 128, 130, 149
Chrome-vanadium steels, 130
Clay for filling, 55
,, Shrinkage of, 141
Clouet, Carburising with diamonds, 82

Digitized by Google

Coal in carburising mixtures, 55, 82
Coarse structure, 7, 68
Cohesion, Inter-crystalline, 24
Coke, Carburising with, 82
Compression cracks, 145
Conductivity of mixtures, 54, 90
Cone test, Ludwig, 98
Contraction, 138, 148
Cooling, Effect of rate of, 60, 117, 119, 135, 138
Copper plating, 56
Core, Brittleness in, 7
,, Fibrous, 19, 24
Cored boxes, Objections to, 52
Corners, Sharp, 109, 129, 138
Cracks caused by cementite, 34
,, ,, slag streaks, 40
,, ,, soft places, 49
,, ,, sulphide, 93
,, ,, unequal expansion, 138
Cracks, Compression, 145
,, Creeping, 110
,, Ring, 113
,, Shrinkage, 143
,, Transverse, 29
Crane hooks, Brittle, 61
Creeping cracks, 110
Crucible making, 141
Crystal formation, 138
Crystalline fractures, 24, 106
Cutter teeth, Splintering of, 144
Cutting flame, 162

Deakin, E. A., on properties of mild steel, 121
Decarburisation, 45, 58, 152
Depth of penetration, 38, 62
Design, Faulty, 34
Diagram, Equilibrium, 77
Diamond, Carburising effect of, 82
Dies, Case-hardened, 42
,, Decarburisation of, 94
Diffusion, 11, 36, 38, 58, 77
Discrepancies, 88
Distortion, 24, 29, 105, 108, 113, 138, 148
Double quenching, 19, 25
Drifts, 1
Drop forgings, 69, 158
Dyson, W. H., on addition of sawdust, 91

Elastic limit, Influence on impact test, 105
Electrically heating, 161, 162
Equilibrium, 11
,, diagram, 77
Etching test, 42, 146
Expansion, 49, 138, 148

Ferrite, 6, 15, 31
Ferro-cyanide in carburising mixtures, 83, 89
Ferro-cyanide in sprinkling powders, 94
Fibre, Harmful, 41
,, Production of, 19
,, What is, 24
Files, Case-hardened, 1
,, Hardening, 44
,, Testing machines for, 71
,, ,, with, 95
Final quenching, 26
Firebrick in carburising mixture, 83
Flaking, 40
Flame cutting, 162
Flour in carburising mixtures, 89
,, sprinkling powders, 94
Fluids, Quenching, 158
Freckled corners, 38, 65
Fremont impact test, 103
Furnaces, Carburising, 51
,, Hardening and tempering, 151
Fused silica tubes, 153

Gaseous carburisers, 93
Gases, Action of, 58, 81
Gauges, 1
Gears, Harmful fibre in, 41
,, Machining of, 66
,, Nickel-chrome steel, 76, 135
,, Surface hardening, 163
Graphite, Deposition of, 91
,, in "Blackheart" malleable castings, 82
Grayson on sulphur in charred leather, 93
Greasy carburisers, 87
Grinding, 46, 50
Guillery impact machine, 103

Hair in carburising mixtures, 83
Hardened case, Strength of, 111
Hardening, 137
,, Blowpipe, 162
,, plant, 151
,, press, 161
"Hardenite," 54
Hardness, Brinell, 99
,, Loss of, 150
,, Testing, 95
Heat treatment, Changes by, 118
"Heat Treatment of Tool Steel," 137, 156
Heyn and Bauer on loss of hardness, 150
Horn in carburising mixtures, 83
Hornmeal in sprinkling powders, 94
Huntsman process, 3

Digitized by Google

Hydrocarbonated bone black, Conductivity of, 55
Hydrocarbonated bone black, Vaseline from, 87
Hyposulphite, Surfusion in, 133

Impact testing, 28, 61, 103, 114
Indicators, Temperature, 154
Ingot iron, 28
Inter-diffusion, 11, 36, 38, 58, 77
Iron carbide, 3, 6, 34, 58, 60, 78
,, sheaths for thermo-couples, 153
Izod impact tester, 103

Lamination, 24, 27, 30
,, of pearlite, 5, 17
Lids for boxes, 52
Limestone, Conductivity of, 55
Ludwig cone test, 98

Machined surfaces, 66
Machine spindles, Material for, 75
MacIntosh on use of coal gas, 93
Magnetic changes, 135
Malleable iron castings, 2, 82
Manganese, Effect of, 60, 69
,, steels, 70, 127
Marguerite on carburising effect of diamond, 82
Martensite, 74, 162
Mass, Effect of, 117
Material, Selection of, 125
Maurer on loss of hardness, 150
Mechanical properties, according to constituents, 6
Mechanical properties, Buying, 124
,, ,, Calculation —from Brinell hardness numerals, 99
—of crane hook, 62
—of mild steel, 121
—of carbon steels, 127, 130
—of nickel steels, 127, 130
—of nickel-chromium steels, 76, 123, 128, 130
—of tempered steel, 150
Melting process, Effect of, 117
Micro-sections, Preparation of, 64
Mild steel, Mechanical properties of, 121
Mixtures, Carburising, 54, 77
Moisture in carburising mixtures, 83, 93
Nead and Bourg on conductivity of mixtures, 55
Nickel plating, 56
,, steel, Guillet's diagram of, 72
,, ,, Mechanical properties of, 29, 127, 130
Nickel-chrome steels, Mechanical properties of, 29, 75, 123, 128, 130, 149
Nolly and Veyret on carburising gases, 83
Notched bar tests, 28, 61, 102, 114

Oil for hardening purposes, 159
,, in carburising mixtures, 55, 87, 89, 90
,, quenching, Distinction of case after, 62
,, ,, Efficiency of, 159
,, ,, from high heats, 120
,, ,, steels rich in manganese, 71
,, ,, to produce fibred cores, 26
Optical pyrometer, Use of, 51
Osmond on carburising effect of diamond, 82
Overheating, 7, 120
Oxy-acetylene heating, 161, 162

Paste, Case-hardening, 1
Pearlite, 5, 17
Penetration, Depth of, 62
Pepys on carburising effect of diamond, 82
Petroleum residues in carburising mixtures, 89
Phosphorus in charred bone, 91
Physical properties, 117
Pins, Material for, 66, 70
Piston head, Fractured, 109
,, pins, Grinding, 46
,, ,, Material for, 41
Plant, Hardening and tempering, 151
Plaster of Paris in carburising mixtures, 83
Platinum thermo-couples, 153
Porcelain tubes for pyrometers, 153
Porosity of carburising mixtures, 90
Portevin and Beriot on diffusion, 38
Potassium bichromate in carburising mixtures, 89
Potassium cyanide baths, 94
,, ferro-cyanide in carburising mixtures, 83, 89
Potassium ferro-cyanide in sprinkling powders, 94
Powders, Sprinkling, 94
Press hardening, 161
Presses, Hand, 112
Protection for thermo-couples, 153
Prussiate of potash in carburising mixtures, 83, 89
Prussiate of potash in sprinkling powders, 94

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Pyrometers, 8, 51, 87, 152

Quartz in carburising mixtures, 83
Quenching, Double, 19, 25
,, fluids, 158
,, temperatures, 21, 120

Rape oil, Efficiency of, 159
Rate of cooling, Effect of, 60, 117, 119, 135, 138
Razor blades, Hardening, 161
Reagents, Carburising, 77
Reamers, Case-hardened, 1
,, Hardening, 26
Reaumur process, Cast steel, 3
,, ,, malleable castings, 2
Recalescence point, 9, 79, 131, 138, 155
Recording pyrometers, 8, 54, 87, 154
Refining, 8, 35, 77, 137
Resin in carburising mixtures, 89
,, sprinkling powders, 94
Ring cracks, 113
Roberts-Austen on carburising effect of, diamond 82
Rolling, Effect of, 118
Rough finish, Cause of, 67
Round notches in impact tests, 108

Salt in hardening paste, 1
,, ,, carburising mixtures, 83, 89
,, ,, sprinkling powders, 94
,, bath furnaces, 94, 152
Saltpetre in carburising mixtures, 89
Sand, Retarding action of, 57, 83
Sawdust in carburising mixtures, 89, 90, 91
Saw hardening 161
Schafer, Dr., case-hardened section of, 64
Sclerometer test, 150
Scleroscope test, 96
Screws, Material for, 66
Seams, 28
Segregates, 139
Selection of materials, 125
Sentinel pyrometers, 51, 156
Shape, Effect of, 117
Sharp corners, 109, 129
Shear steel, 3
Shock resisting, 23, 28
Shrinkage, 141
,, cracks, 143
,, of carburising mixtures, 90
Silica tubes for thermo-couples, 153
Silicon, Effect of, on cast iron, 52, 60
,, ,, ,, case-hardening steels, 69
Slag streaks, 4, 27, 31, 40, 70
Slow cooling, Effect of, 60
Soda ash in carburising mixtures, 83, 89, 90
Sodium acetate, Surfusion in, 133
,, carbonate, Conductivity of, 55
Sodium carbonate in carburising mixtures, 83, 89, 90
Sodium hyposulphite, Surfusion in, 133
Soft places, 42, 49, 55
,, ,, on balls, 146
Solid carburisers, 81
,, solution, 17
Soot in carburising mixtures, 83, 89
,, sprinkling powders, 94
Sparks, Grinding, 46
Specific heat of oil, 159
Spindles, Material for machine, 75
"Splash of a Drop, The," 147
Splinters, 49, 144
Sprinkling powders, 94
Stead, Dr., hardening diagram, 80
,, ,, troostite in file, 43
Steel boxes, 52
,, Hardness of bar, 101
,, Toughness of bar, 102
Steels, Case-hardening, 66
,, Selection of, 125
Streaky troostite, 48
Structural changes, 7
Structure of steels, 4
Sulphur in charred leather, 93
Sumpter's patent surface hardening, 163
Supercarburisation, 38
Surface hardening, 161
Surfaces, Machined, 66
Surfusion, 133
Swedish iron, Use of, 116

Tantalum steels, 131
Taper heating, 164
Taps, Hardening, 26
Tar in sprinkling powders, 94
Tartaric acid in sprinkling powders, 94
Temperature of cementation, 7, 80, 90
,, ,, quenching, 21, 120
Temperature of refining case, 8, 35, 77, 136
,, ,, ,, core, 8, 77
,, indicators, 154
,, recorders, 154

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Tempering process, 149
,, ,, effect on alloy steels, 122
Tempering process, effect on mechanical properties, 120
Tensile strength, calculation from Brinell hardness, 99
Tensile strength of tempered steel, 150
Testing hardness, Methods of, 95, 111, 150
Thermo-couple, Protection of, 153
,, Utility of, 8, 51, 54, 87, 156
Titanium steel, 29, 131
Tool marks, Effect of, 109
Toughness, 102, 110
Transverse cracks, 29
Troostite, 43, 48, 162
Tungsten, Effect of, 69

Uranium steels, 131

Vanadium, Effect of, 130
Vaseline from hydro-carbonated bone black, 87
Vegetable fibre in carburising mixtures, 83
Vegetable husks in carburising mixtures, 83, 89, 90
Veyret and Nolly on carburising gases, 83
Vickers and Sumpter's patent surface hardening, 163
Vismara on oil gas, 93

Waggon spring steel, 29
Warping, 26
Water, Speed of cooling in, 158
Wearing qualities of steel, 71
Welding, Blowpipe, 161
Whale oil, Speed of cooling in, 159
White surface, 90
Wire ropes, Surface hardening of, 161
Wood charcoal, Conductivity of, 55
,, ,, in carburising mixtures, 83, 90
Worthington, Prof., on "The Splash of a Drop," 147
Wrought iron, Slag in, 28

Yield point influence on impact test, 105

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